keV, MeV, and PeV signals
from Neutrinos and
Dark Matter

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Johns Hopkins University

w/ H.An, M.Kamionkowski, M.Pospelov

INFO 2013
Santa Fé, NM

Outline

- PeV and keV neutrino signals

  the "neutrino-oscillation portal"
  and enhanced interactions of new neutrinos

- MeV dark matter signals

  neutrino experiments as dark matter detectors,
  in particular searches for 0ν2β decay

PeV signals from neutrinos

...preliminary explorations

w/ M. Kamionkowski and M. Pospelov

IceCube
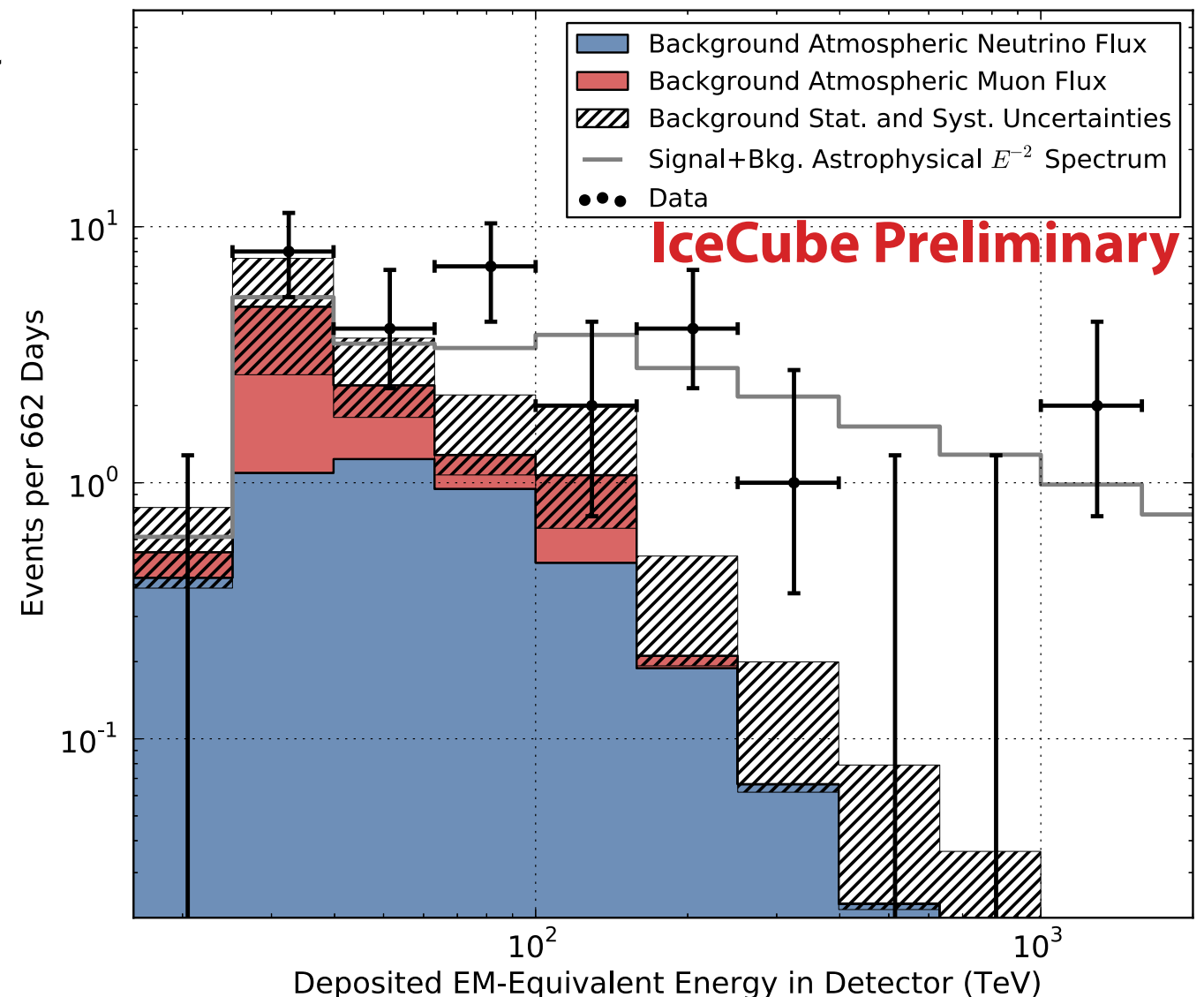## high energy neutrino flux

Aartsen et al. 2013
talks by Whitehorn and Kopper @ IPA2013, ...

- IceCube IC-79/IC-86 2 year data

  2 events at PeV energy

  26 more event 20-200 TeV
  (follow-up analysis)

- Highest energy neutrino events ever observed
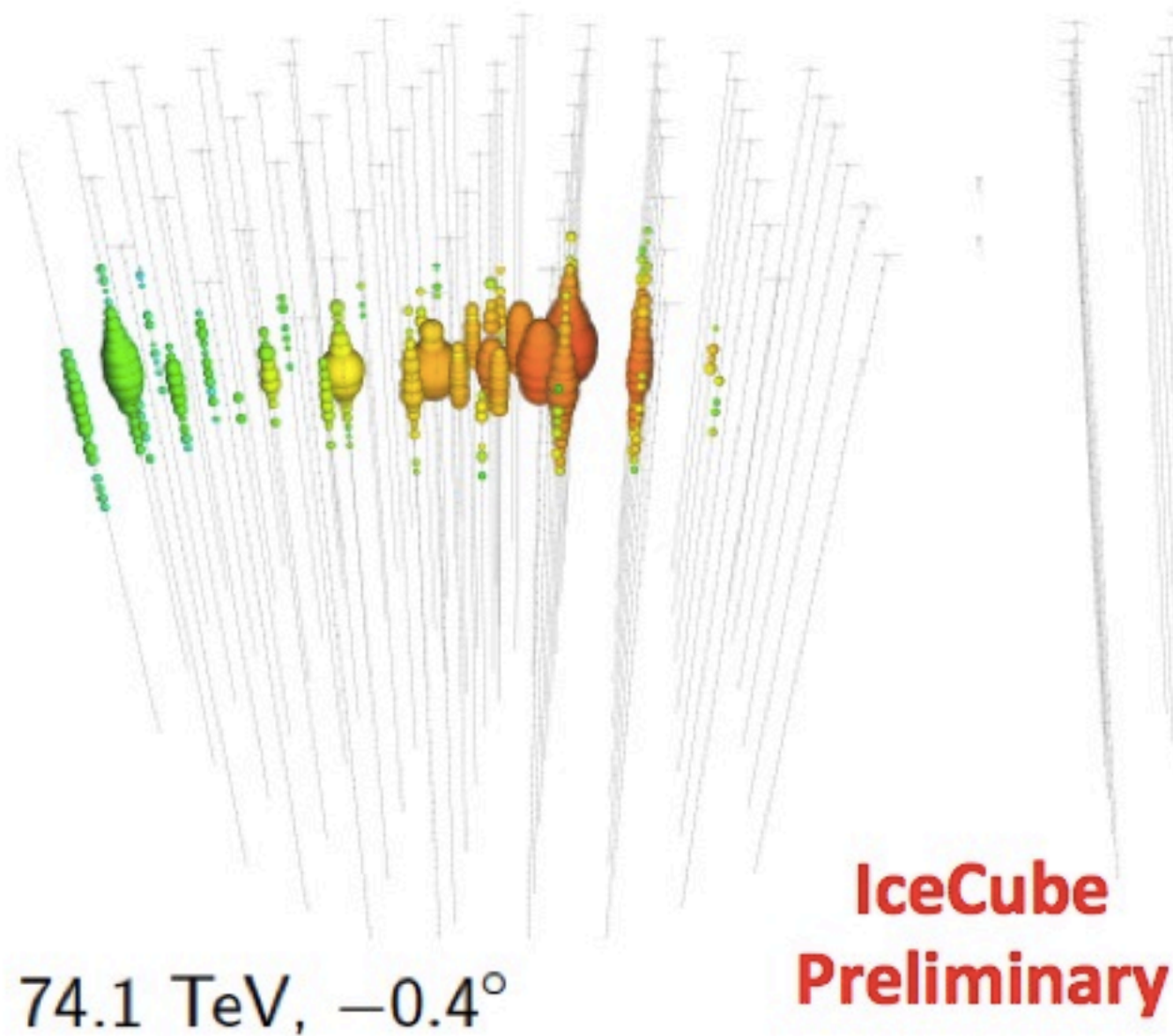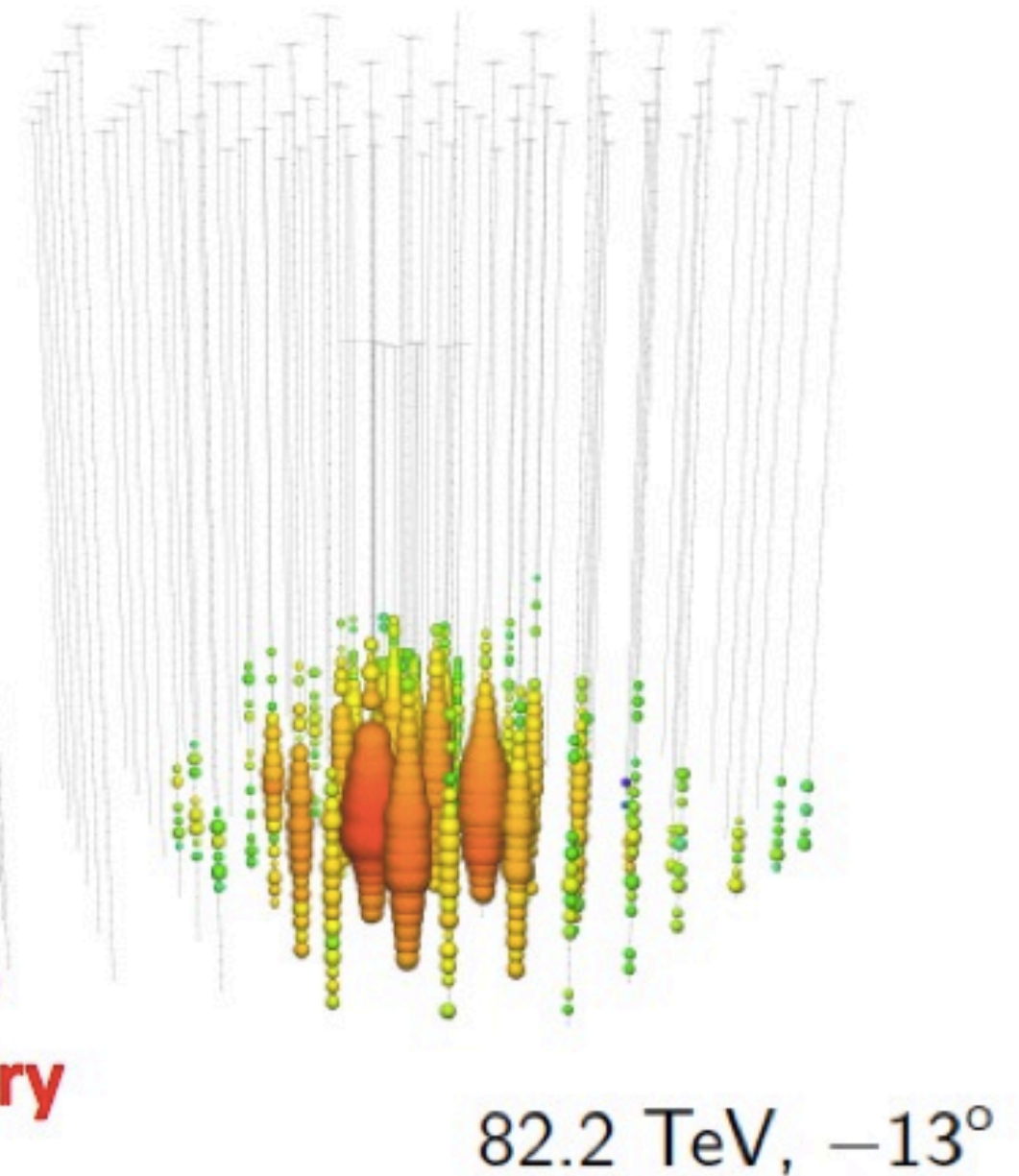
- First indication of extragalactic neutrino flux

IceCube Preliminary

Legend:
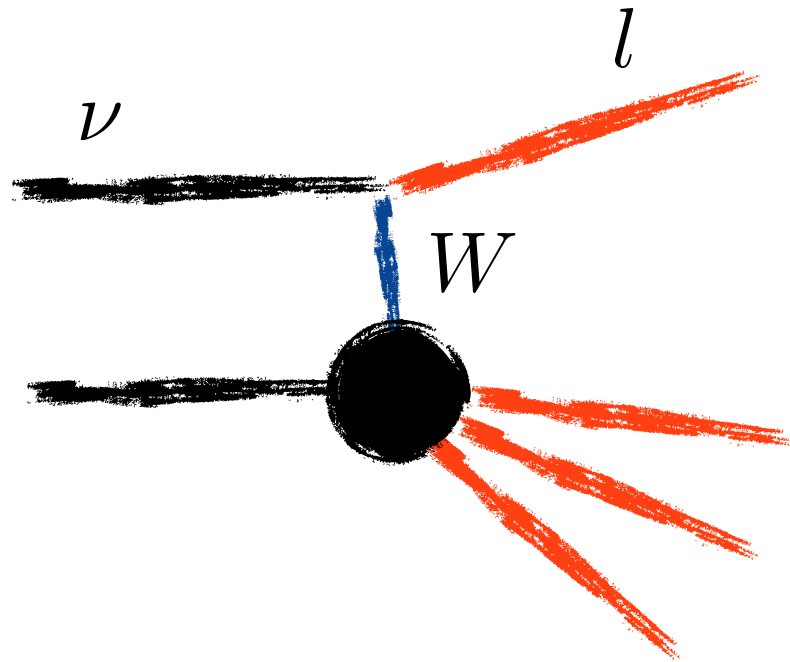- Background Atmospheric Neutrino Flux
- Background Atmospheric Muon Flux
- Background Stat. and Syst. Uncertainties
- Signal+Bkg. Astrophysical E^{-2} Spectrum
- Data

Events per 662 Days

Deposited EM-Equivalent Energy in Detector (TeV)

IceCube
event topologies

track   **shower**

74.1 TeV, −0.4°   IceCube Preliminary   82.2 TeV, −13°

IceCube
event topologies

CC

NC

l

ν

W

ν

ν

Z

ν_μ ...tracks

ν_x ... showers
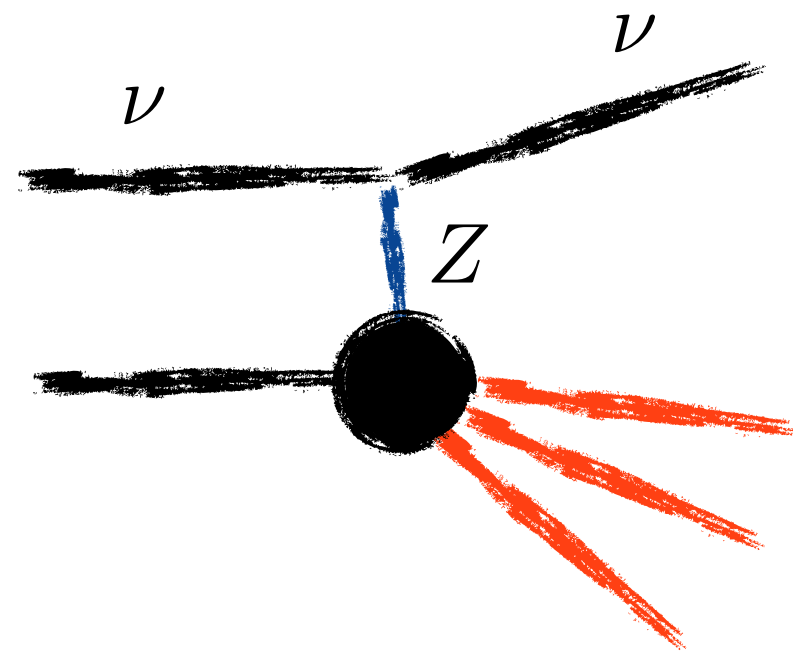
$\sim 40\%$ of E_ν deposited

$\nu_{e,\tau}$ ...showers
  (for sub-PeV ν_τ)
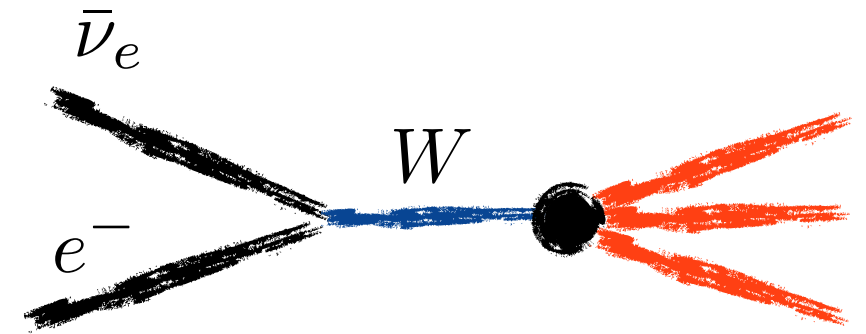
IceCube
reported features

Glashow resonance

Aartsen et al. 2013
talks by Whitehorn and Kopper @ IPA2013, ...
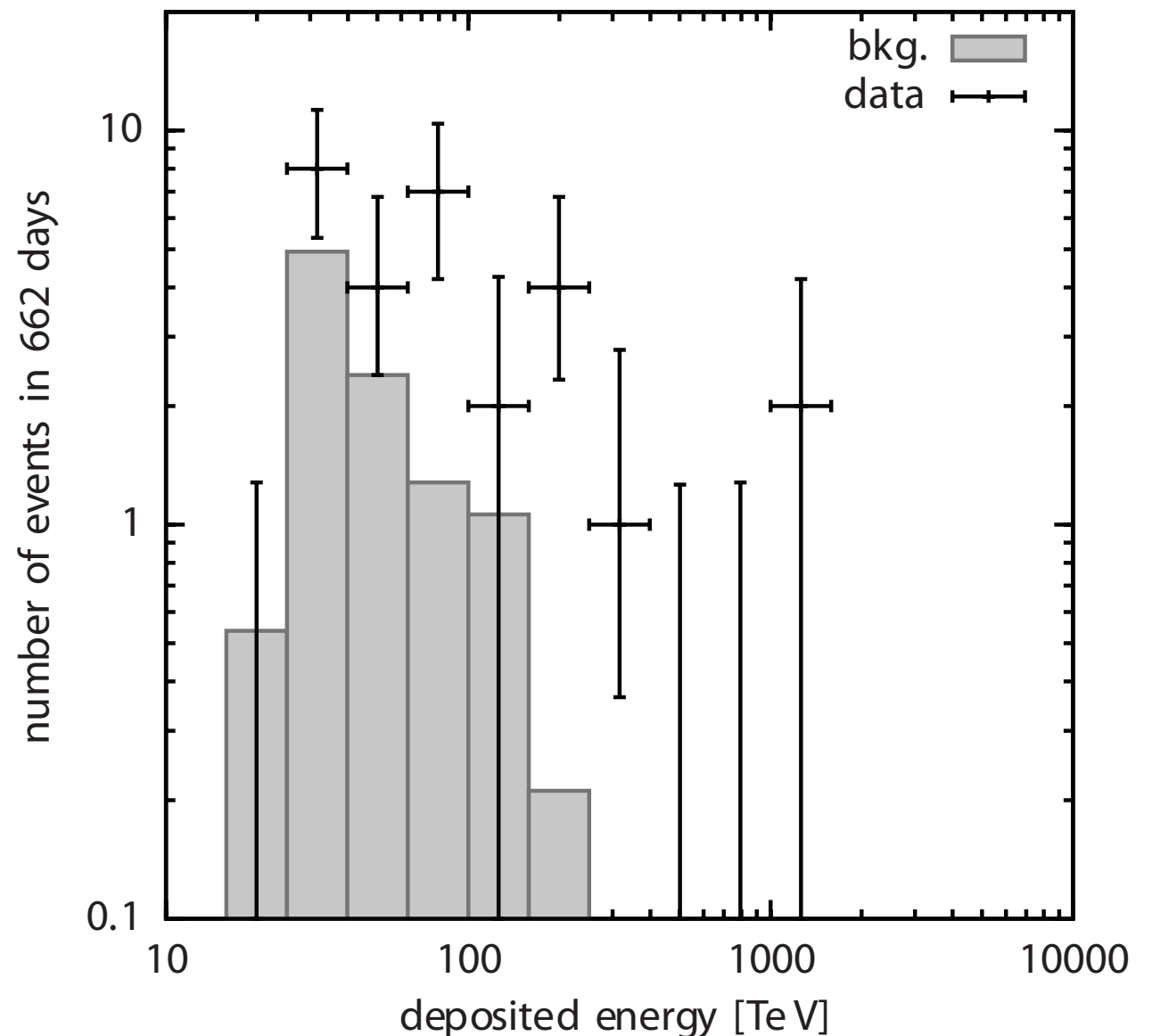
- harder spectrum than expected
  from atm. backgrounds (4σ)

- consistent with isotropic flux

- **potential cutoff above**
  ~ 2 PeV?

  where is the Glashow
  resonance @ 6.3 PeV?
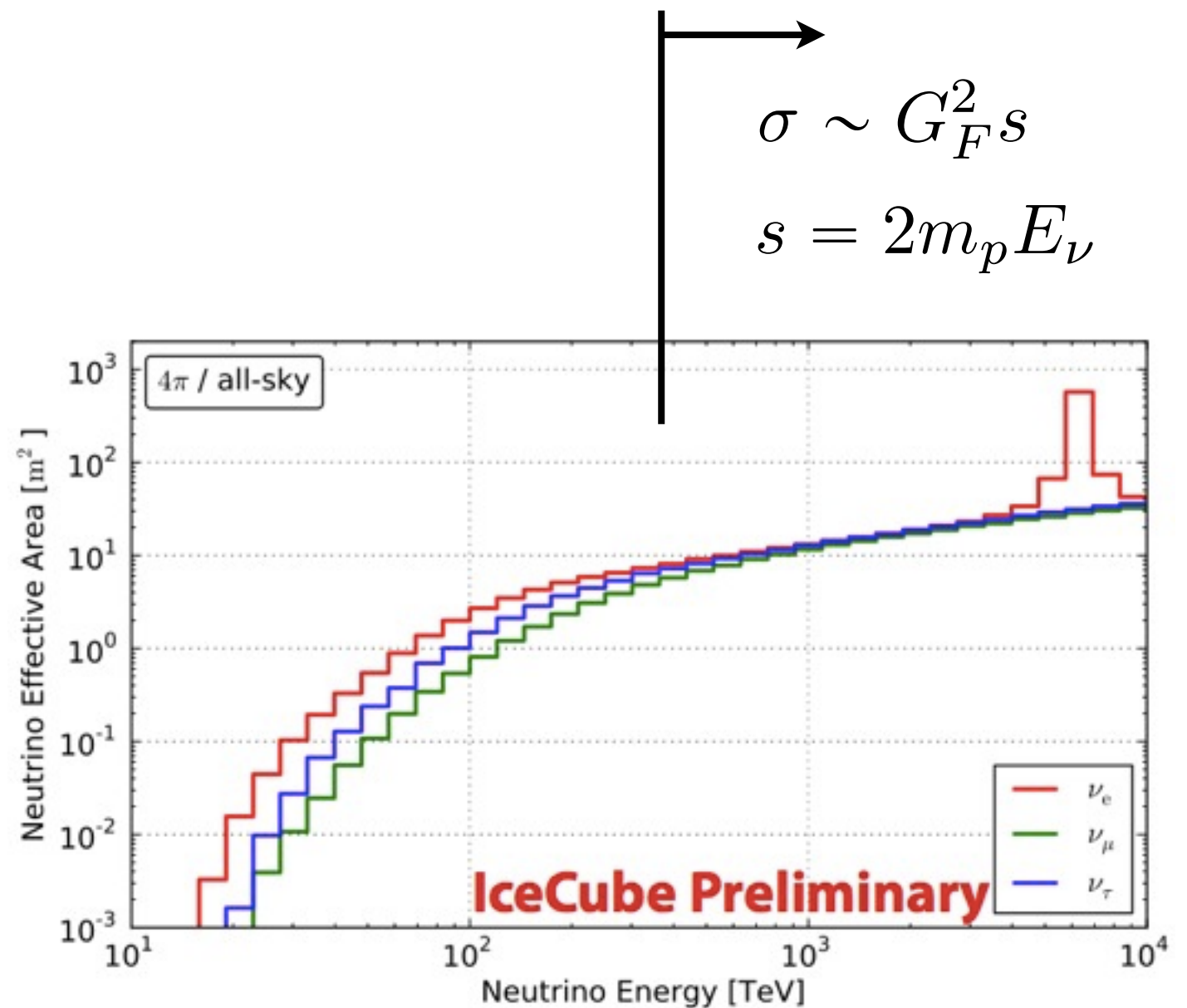
  $$m_W = \sqrt{2 m_e E_\nu}$$

IceCube
required flux

- Flux and spectral index:

$$\Phi_\alpha^d = 4\pi \phi_0 f_\alpha \left(\frac{E_\nu}{1\,\mathrm{TeV}} \right)^{-\gamma}$$

fraction in flavor α

=> assuming all nu in
e-flavor gives a more
conservative flux estimate

$$\sigma \sim G_F^2 s$$
$$s = 2 m_p E_\nu$$

Neutrino Effective Area [m²] vs Neutrino Energy [TeV]
4π / all-sky
IceCube Preliminary
ν_e, ν_μ, ν_τ

IceCube
required flux

- Flux and spectral index:

$$\Phi_\alpha^d = 4\pi \phi_0 f_\alpha \left(\frac{E_\nu}{1\,\mathrm{TeV}} \right)^{-\gamma}$$

↑

fraction in flavor α

=> assuming all nu in
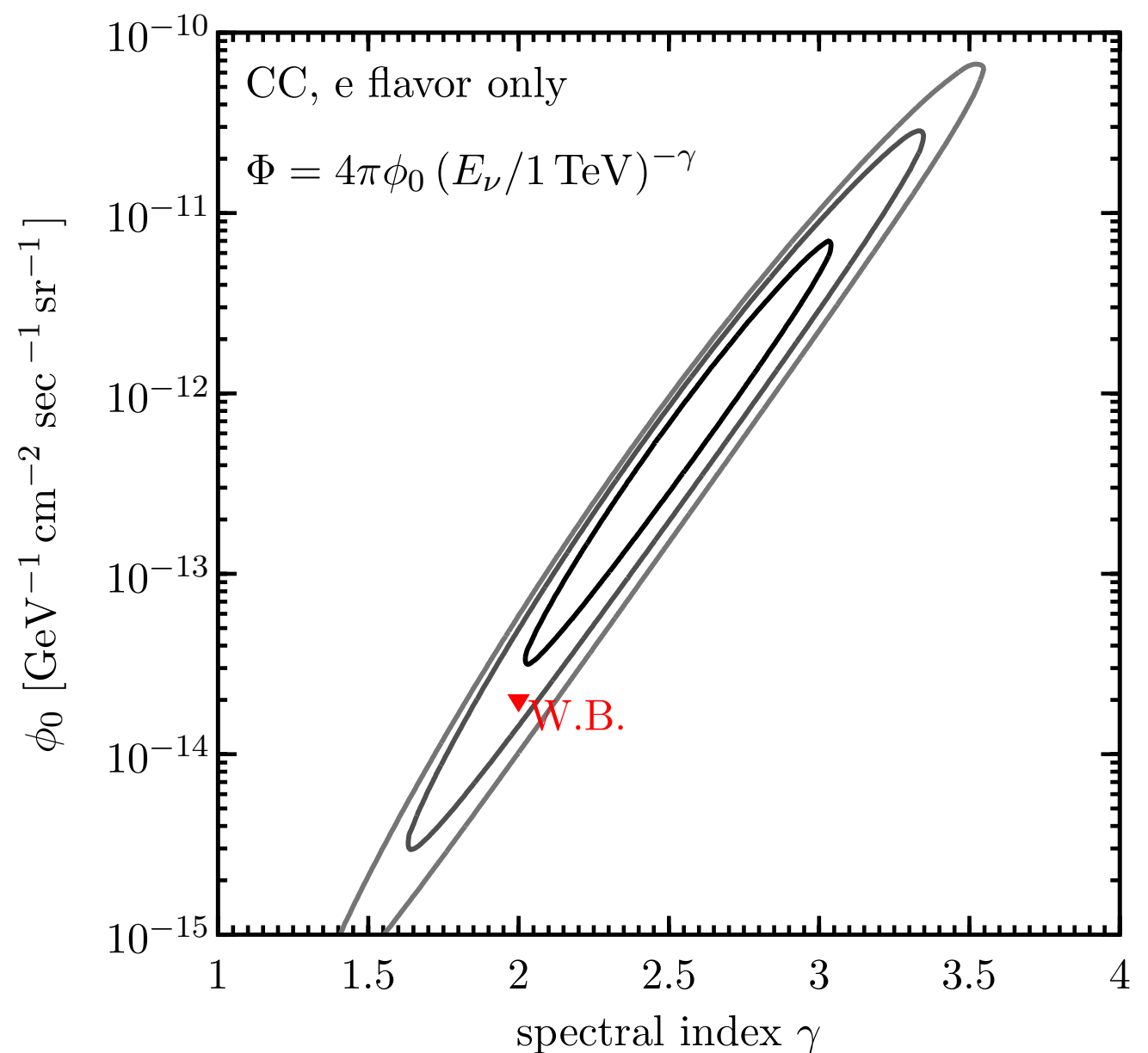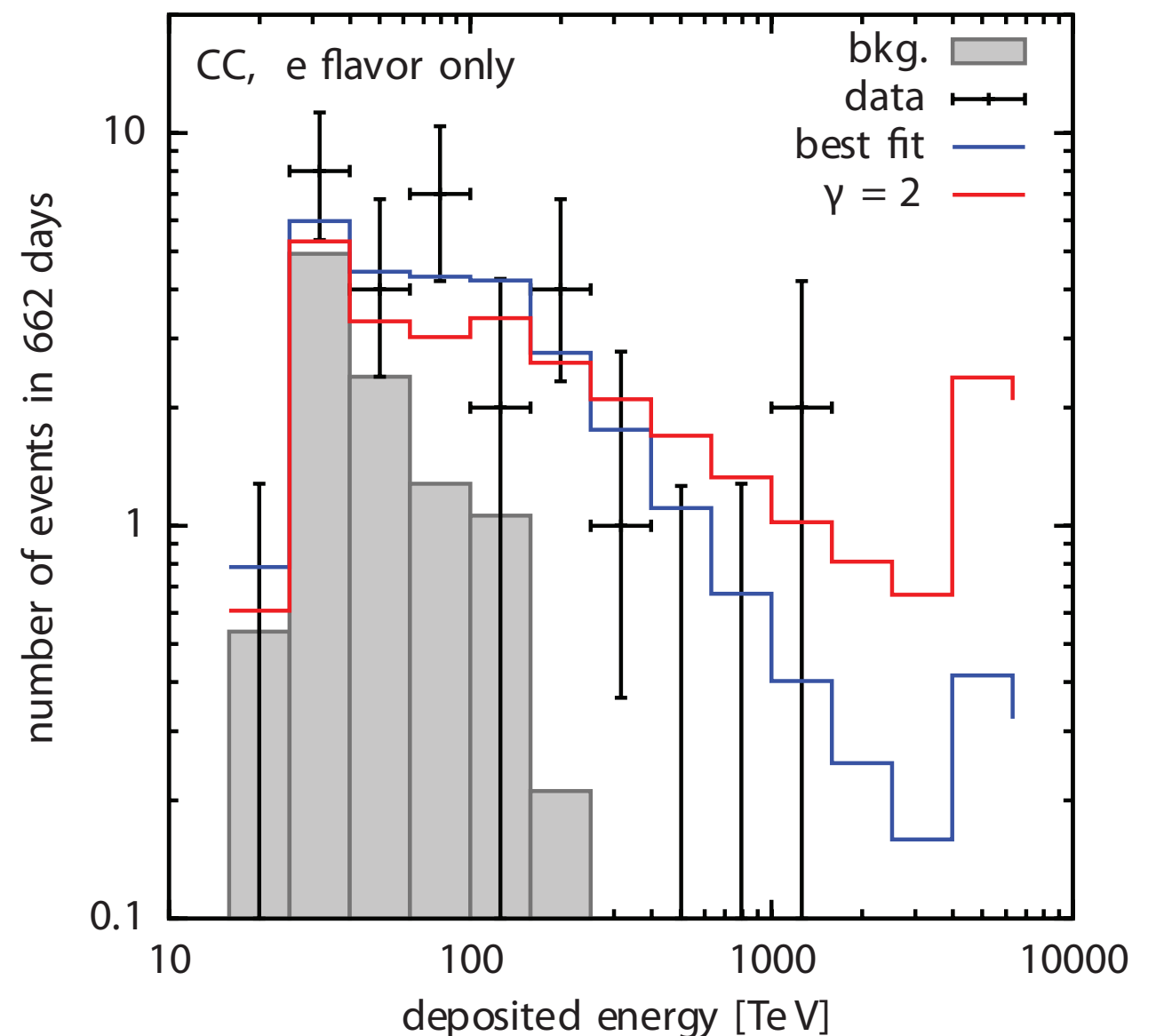e-flavor gives a more
conservative flux estimate

IceCube
required flux

- Flux and spectral index:

$$\Phi_\alpha^d = 4\pi \phi_0 f_\alpha \left(\frac{E_\nu}{1\,\mathrm{TeV}} \right)^{-\gamma}$$

↑

fraction in flavor α

=> assuming all nu in e-flavor gives a more conservative flux estimate

CC, e flavor only

bkg.
data
best fit
γ = 2

number of events in 662 days

deposited energy [TeV]

Origin of PeV neutrinos

- (extragalactic) CR generated neutrino flux

$$p + p \rightarrow [\pi^0 + \pi^+ + \pi^-] + X,$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$$

flavor ratios at source

$$\phi^s_{e+\bar{e}} : \phi^s_{\mu+\bar{\mu}} : \phi^s_{\tau+\bar{\tau}} = 1 : 2 : 0$$

flavor ratios at detector

$$\phi^d_\beta = P_{\beta\alpha} \phi^s_\alpha$$

$$\phi^d_{e+\bar{e}} : \phi^d_{\mu+\bar{\mu}} : \phi^d_{\tau+\bar{\tau}} \simeq 1 : 1 : 1$$

- high-energy neutrino flux limited by Waxman-Bahcall bound

$$E_\nu^2 \Phi_\nu \lesssim 10^{-8} \, \mathrm{GeV \, cm^{-2} s^{-1}}$$

assumes optically thin sources of high-E protons $\tau_{p\gamma} < 1$

Fermi acceleration of p $\gamma_p = 2$

=> PeV neutrinos come from close the second knee, with same spectral index (pp)

$$E_\nu \sim 0.05 E_p$$

A new window into neutrino physics?

The measurements of the high-E neutrino flux will primarily educate us about the origin of high-E cosmic rays.

see, e.g., Murase et al., Laha et al. Fox et al.

But IceCube, at those energies, may also tell us more about new physics in the neutrino sector. Can we:

- induce signals in excess of the Waxman-Bahcall bound?
- "suppress" events in the Glashow resonance region / spectral cut off?
- change observables like shower/track ratio or sky-distribution?
- relax the relation between diffuse gamma rays and nu-flux?

a reminder of why it's fair to think about *new physics* at this early stage

NEUTRINO MOMENTS, MASSES AND CUSTODIAL SU(2) SYMMETRY *

Howard GEORGI and Michael LUKE

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

1. The problem

Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the solar neutrino data, the apparent
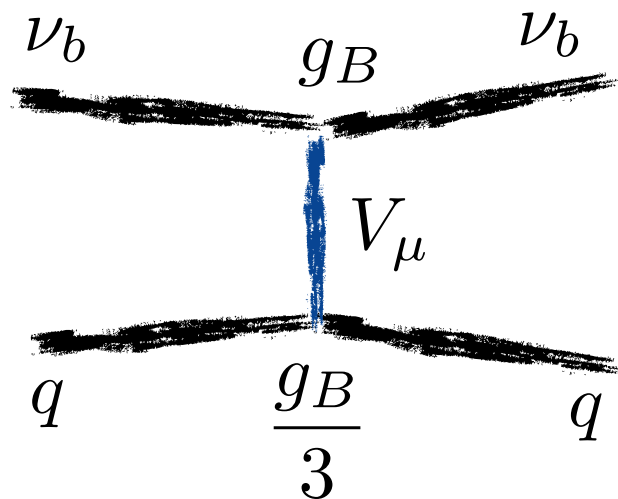
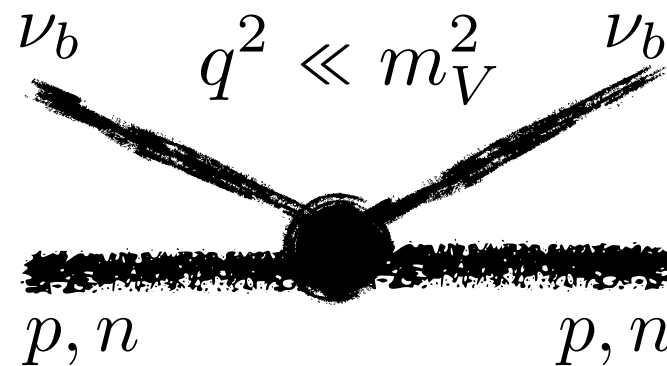# Enhanced interactions with baryonic currents

- new $U(1)_b$ gauge factor, which couples new left-handed neutrino ν_b to quarks but not to leptons via V-type

$$D_\mu \nu_b = (\partial_\mu + i q_\nu g_B V_\mu) \nu_b \qquad \slashed{D} = \slashed{D}^{\mathrm{SM}} + i \frac{g_B}{3} \gamma_\mu V^\mu$$

$$\frac{g_B^2}{m_V^2} \equiv G_B \gg G_F$$

"baryonic neutrino"

- $G_B / G_F \gg 1$ requires light mediator mass $m_V = \mathcal{O}(\mathrm{MeV} - \mathrm{GeV})$
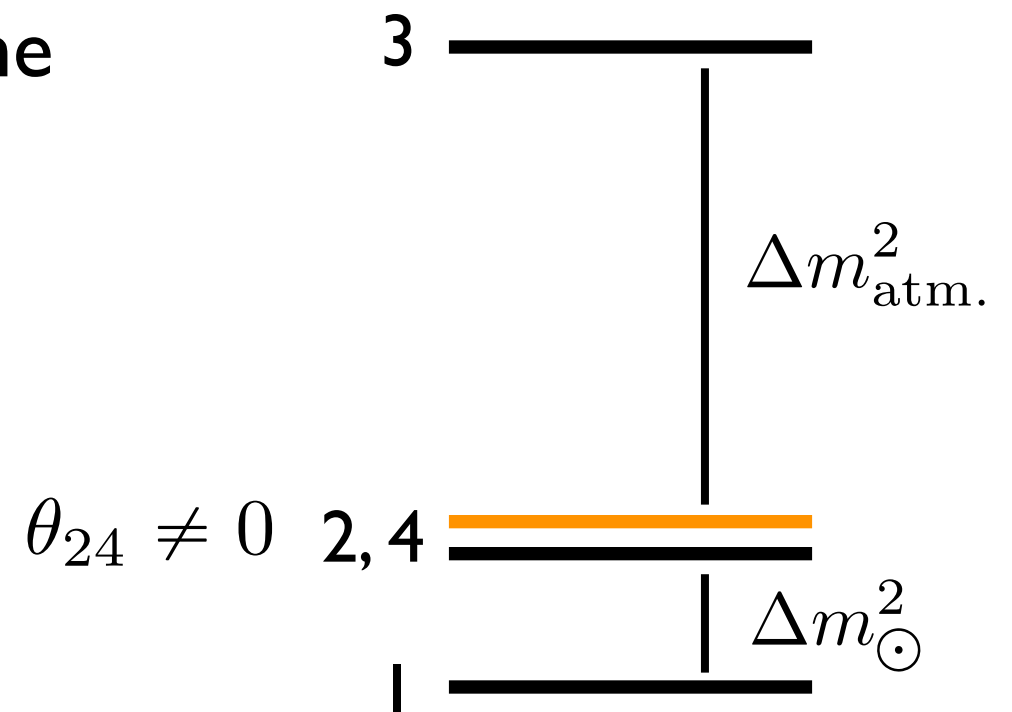
Neutrino oscillation portal

- Δm^2 is the small parameter controlling the appearance probability into a new flavor. Consider, e.g.

$$n_2 = \cos\theta_{24} n_2^0 - \sin\theta_{24} n_4^0,$$

$$n_4 = \sin\theta_{24} n_2^0 + \cos\theta_{24} n_4^0$$

$$U = U_3 R^{24}(\theta_{24})$$

3

$$\Delta m^2_{\text{atm.}}$$

$$\theta_{24} \neq 0 \quad \mathbf{2,4}$$

$$\Delta m^2_{\odot}$$

1

- we consider small new angles $\theta_{i4} \lesssim 0.1$
  in order to keep the standard oscillation picture largely intact
  (this still has to be quantified better)

for constraints on mixing with sterile neutrinos
see, e.g., Kopp et al. 2013

Neutrino oscillation portal

- appearance probability of new flavor **"b"**

$$P_{b\alpha} = \left| \sum_k U_{\alpha k}^* U_{bk} e^{-i\frac{\Delta m_{k1}^2 L}{2E}} \right|^2$$

3 ——————

$\Delta m_{\text{atm.}}^2$

$\theta_{24} \neq 0$ **2, 4** ——————

$\Delta m_\odot^2$

1 ——————

Say, atmospheric splitting dominates
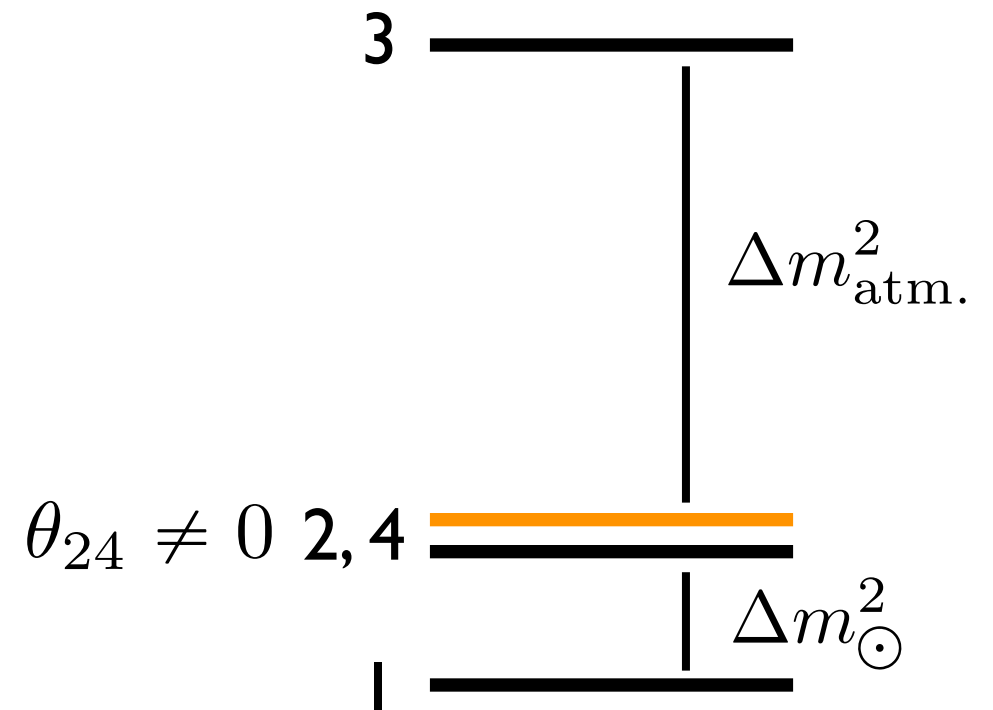
$$P_{b\alpha} = \sin^2\left(2\theta_{b\alpha}^{\text{eff}}\right) \sin^2\left(\frac{\Delta m_{\text{atm.}}^2 L}{4E}\right) \qquad \sin^2\left(2\theta_{b\alpha}^{\text{eff}}\right) = 4\left| \sum_{k>A} U_{\alpha k}^* U_{bk} \right|^2$$

A=1,2,4

$$\sin^2 2\theta_{be,\mu,\tau}^{\text{eff}} = 0$$

small Δm^2 guards new interactions from detection in terrestrial neutrino experiments!

Neutrino oscillation portal

- BUT portal may not guard new interactions on **astrophysical baselines**

$$L_{\mathrm{osc}} = \frac{4\pi E_\nu}{\Delta m^2} \approx 1\,\mathrm{kpc} \left(\frac{10^{-10}\,\mathrm{eV}^2}{\Delta m^2} \right) \left(\frac{E_\nu}{1\,\mathrm{PeV}} \right)$$

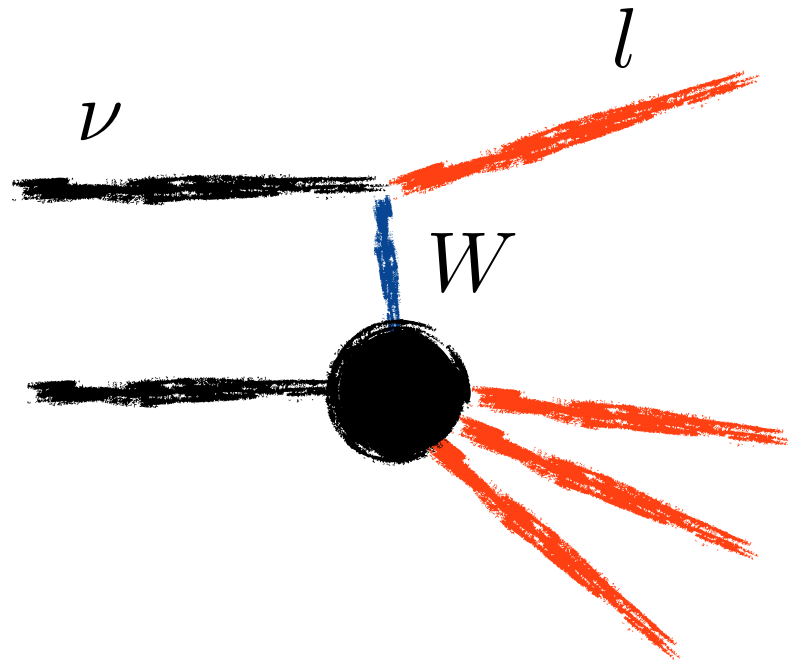- oscillations average out, appearance is incoherent process

$$P_{\beta\alpha} = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{-iE_i t} \right|^2 \rightarrow \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 .$$

$$P_{b\alpha} = \frac{1}{2} |U^{\mathrm{SM}}_{\alpha i}|^2 \sin^2 2\theta_{i4}$$

- IceCube can pick up appearance of the new state!

IceCube event topologies

CC

NC **+ NCB**

ν_μ ...tracks

$\nu_{e,\tau}$ ...showers
(for sub-PeV ν_τ)
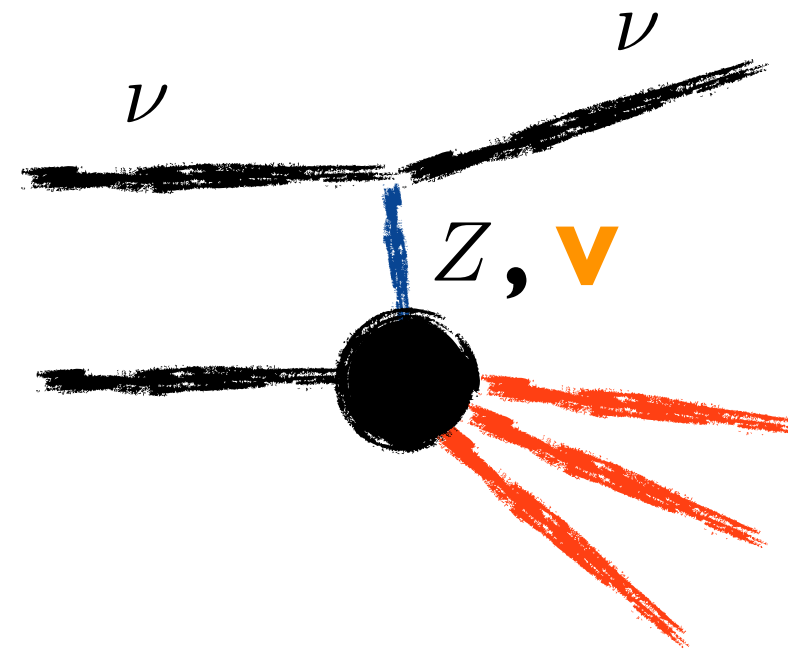
ν_x ... showers
~ 40% of E_ν deposited

+ additional shower events
XX% of E_ν deposited

DIS cross section
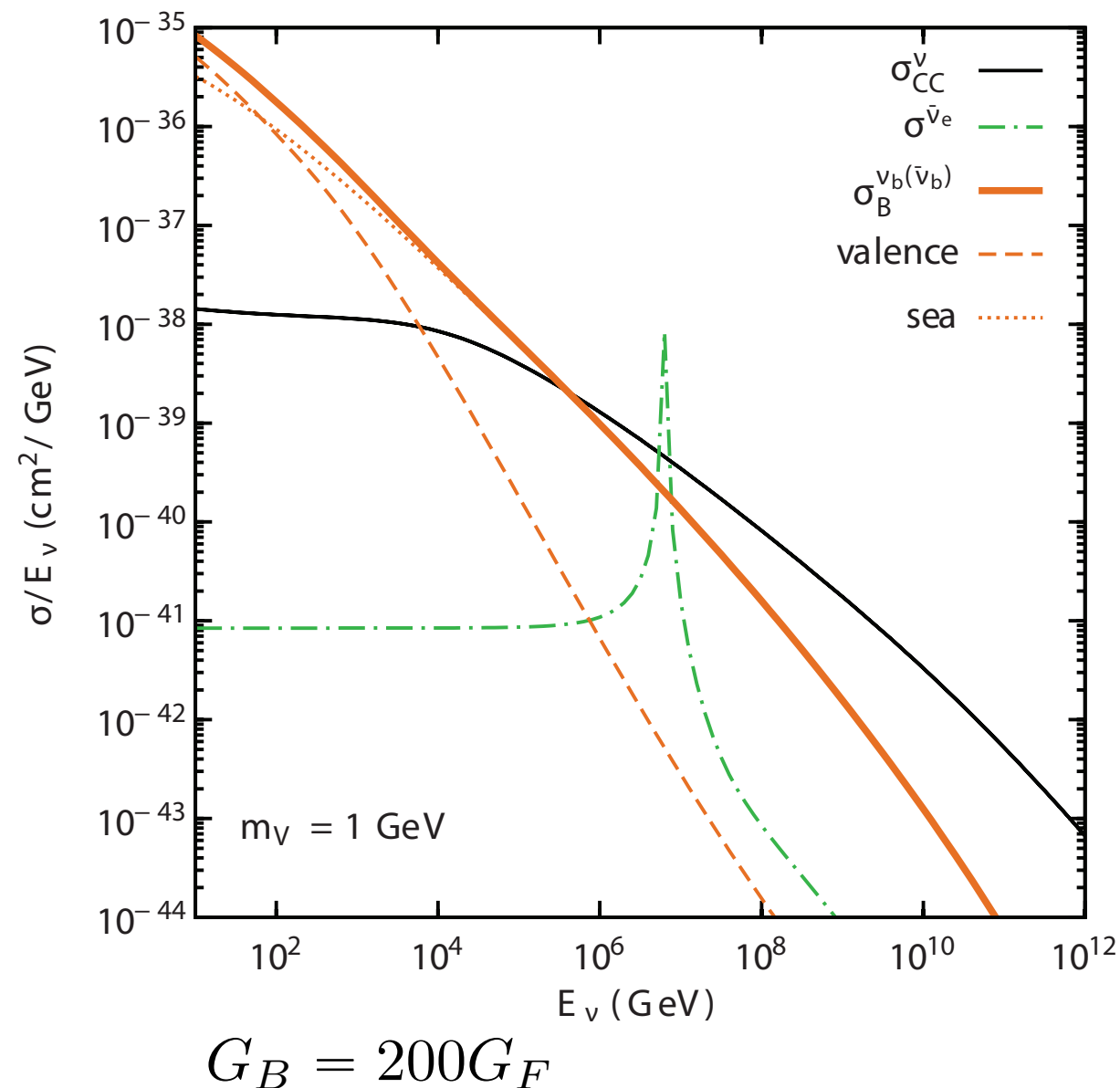
$$\frac{d^2\bar{\sigma}_B}{dxdy} = \frac{G_B^2 q_B^2}{2\pi} \frac{E_\nu m_\mathcal{N}}{(1 + Q^2/m_V^2)^2} \times (\text{"Baryonic Form Factor"})$$
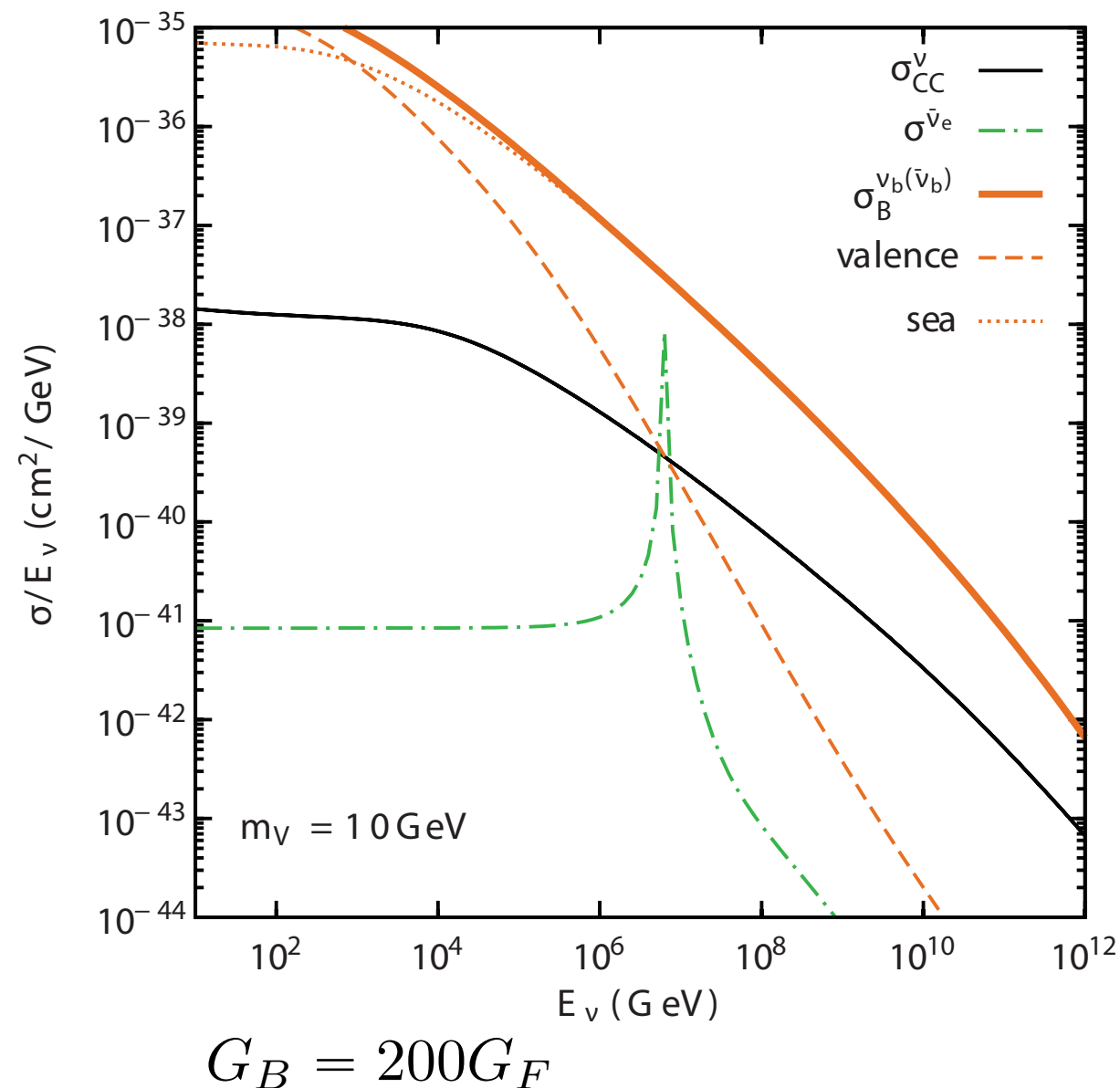

σ_{CC}^ν

$\sigma^{\bar{\nu}_e}$

$\sigma_B^{\nu_b(\bar{\nu}_b)}$

valence

sea

$m_V = 1$ GeV

σ / E_ν (cm^2/ GeV)

E_ν (GeV)

$G_B = 200 G_F$

- A new light mediator V cuts off cross section at lower energies

=> less PeV for more TeV events

=> effective suppression of events in the Glashow resonance region!

DIS cross section

$$\frac{d^2\bar{\sigma}_B}{dxdy} = \frac{G_B^2 q_B^2}{2\pi} \frac{E_\nu m_\mathcal{N}}{(1 + Q^2/m_V^2)^2} \times (\text{"Baryonic Form Factor"})$$

$m_V = 10\,\mathrm{GeV}$

$G_B = 200 G_F$

- A new light mediator V cuts off cross section at lower energies

=> less PeV for more TeV events

=> effective suppression of events in the Glashow resonance region!

DIS average inelasticity
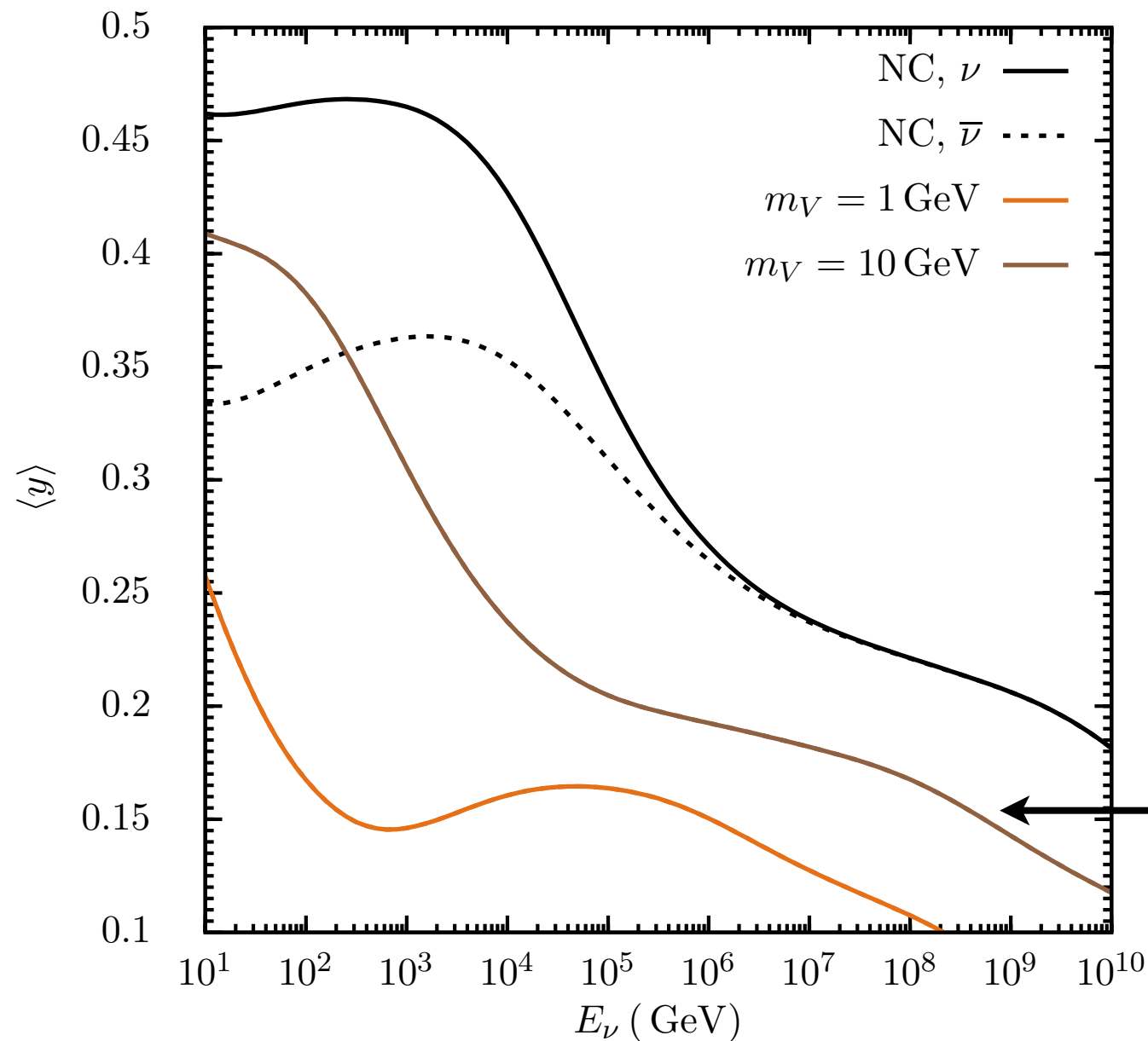
$$y = \frac{E_\nu - E'_\nu}{E_\nu}$$

$\langle y \rangle E_\nu$ ...average energy deposited in the detector

baryonic scatterings are softer than NC

=> heavier mediators are favorable

Event rate

$\Gamma = \text{flux} \times \text{cross section} \times \text{detector efficiency}$

$\sin\theta_{24} = 0.1$
$G_B/G_F = 500$
$m_V = 10\,\text{GeV}$
$\mathcal{N}_{\text{eff}} = 70$

Legend:
- shower (SM+NCB) — solid orange
- shower (SM) — dotted
- track — dashed
- NCB — dash-dot orange

Axes: $E_{\text{vis}}\,dN/dE_{\text{vis}}\ (1/\text{km}^3/\text{yr})$ vs registered energy E_{vis} [TeV]
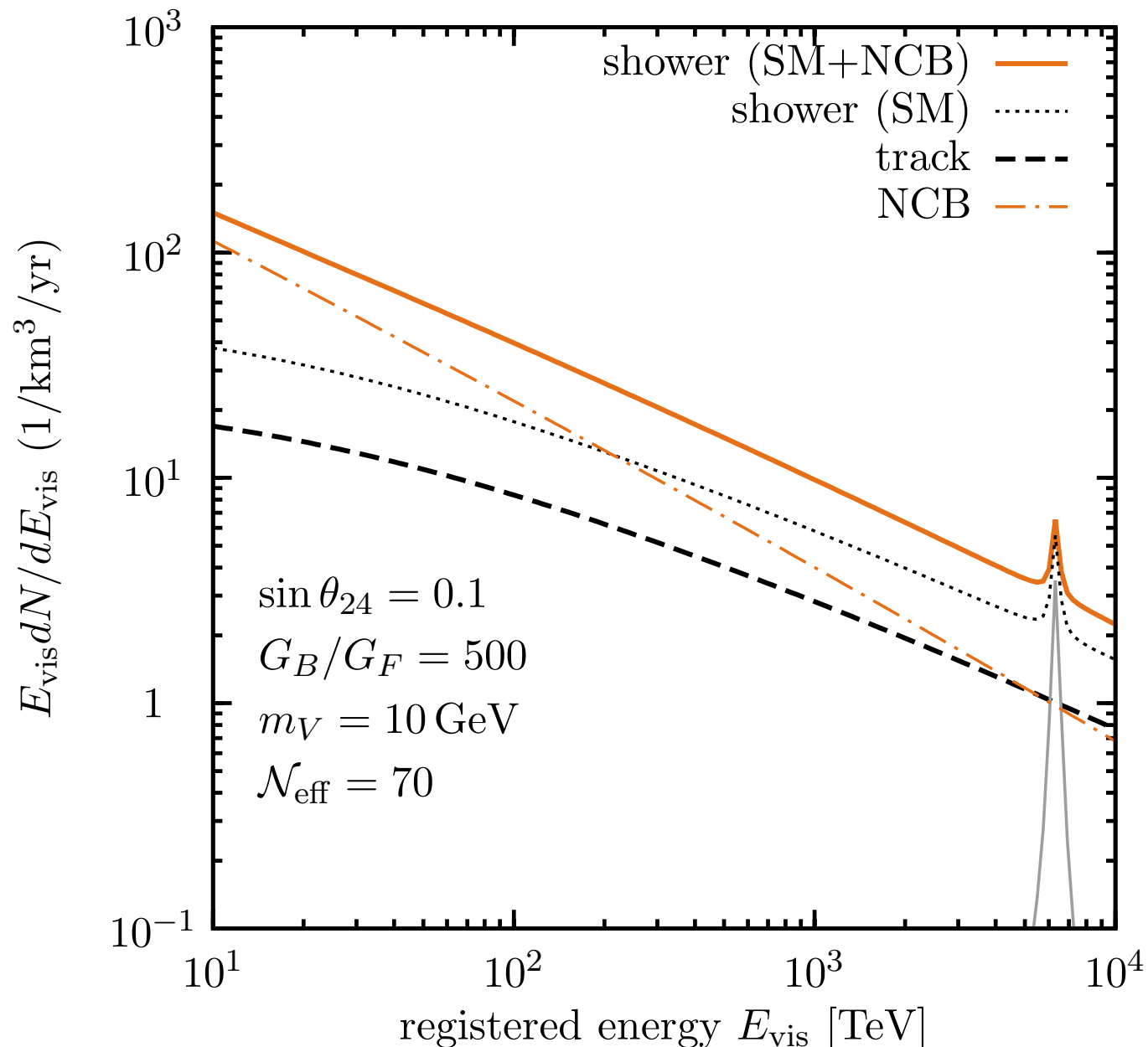
Flux at Detector (d) from CR origin at source (S):

$$\phi^d_\beta = P_{\beta\alpha}\phi^s_\alpha$$

$$\phi^d_{b+\bar b} \simeq \phi^d_{\mu+\bar\mu} \sin^2 2\theta_{i4} \frac{|U^{\text{SM}}_{ei}|^2 + 2|U^{\text{SM}}_{\mu i}|^2}{2P^{\text{SM}}_{e\mu} + 4P^{\text{SM}}_{\mu\mu}}$$

"Softness" of NCB drives one to consider heavier vectors V

IceCube observable shower/track ratios

showers(NCB+SM)/showers(SM)

- $(10 - 10^3)\,\mathrm{TeV}$
- $(10^3 - 10^4)\,\mathrm{TeV}$
- CDF monojet

$\sin\theta_{24} = 0.1$

G_B/G_F

$m_V\ (\mathrm{GeV})$
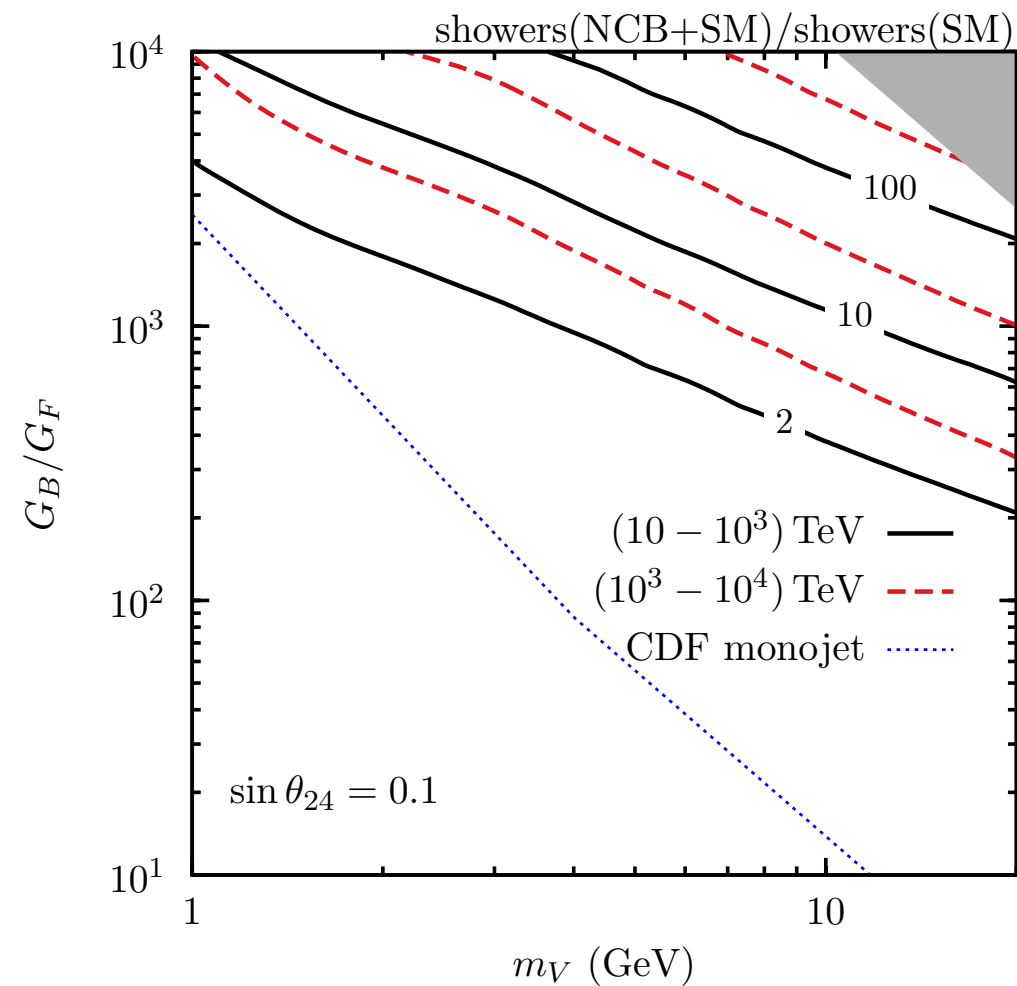
IceCube observable shower/track ratios

Friedland et. al, 2012

showers(NCB+SM)/showers(SM)

G_B/G_F

m_V (GeV)

100

10

2

$(10 - 10^3)$ TeV ——
$(10^3 - 10^4)$ TeV - - -
CDF monojet ·······

$\sin\theta_{24} = 0.1$

CDF ADD

lowPT

veryHighPT

CDF GSNP

highPT

Broad resonance

ε

$M_{Z'}$ [GeV]
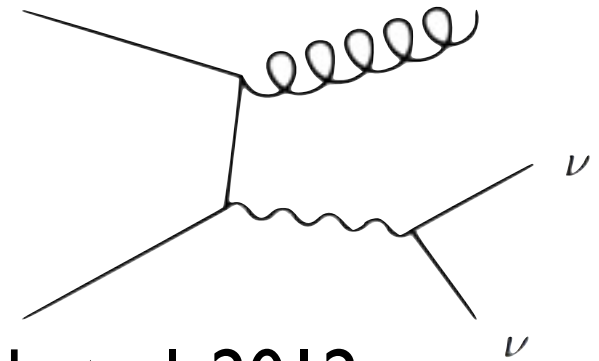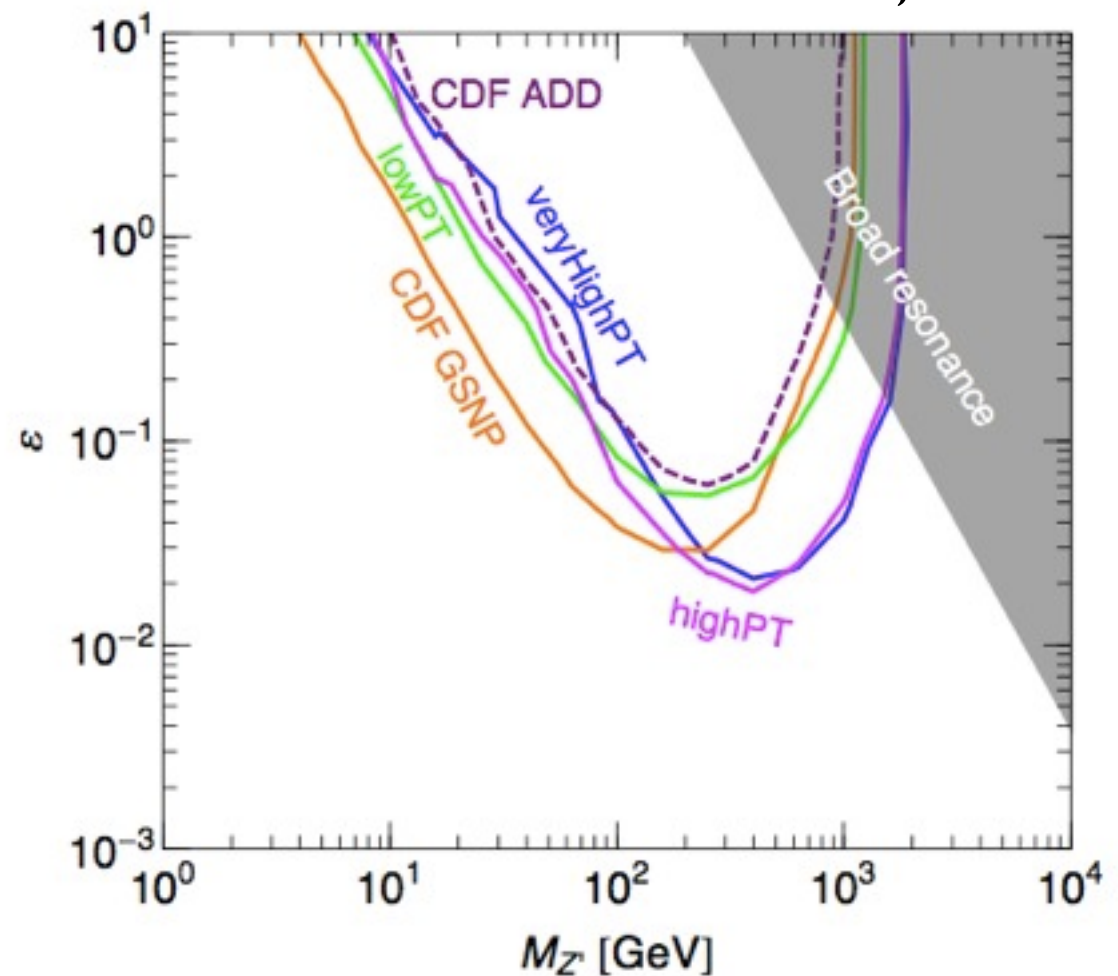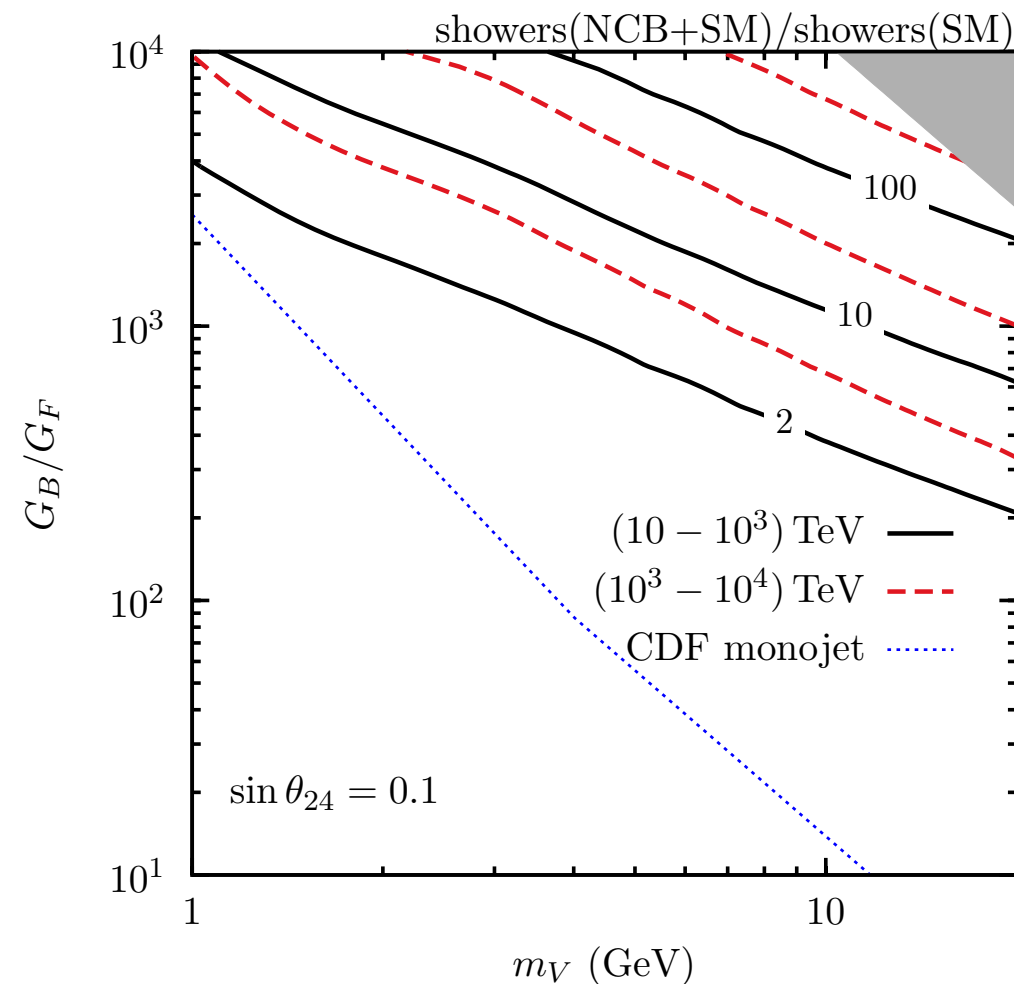
combination of largish vector masses together with large coupling is excluded by collider monojet constraints.

IceCube observable shower/track ratios

showers(NCB+SM)/showers(SM)

$(10 - 10^3)$ TeV —

$(10^3 - 10^4)$ TeV – – –

CDF monojet ·······

$\sin\theta_{24} = 0.1$

G_B/G_F

m_V (GeV)
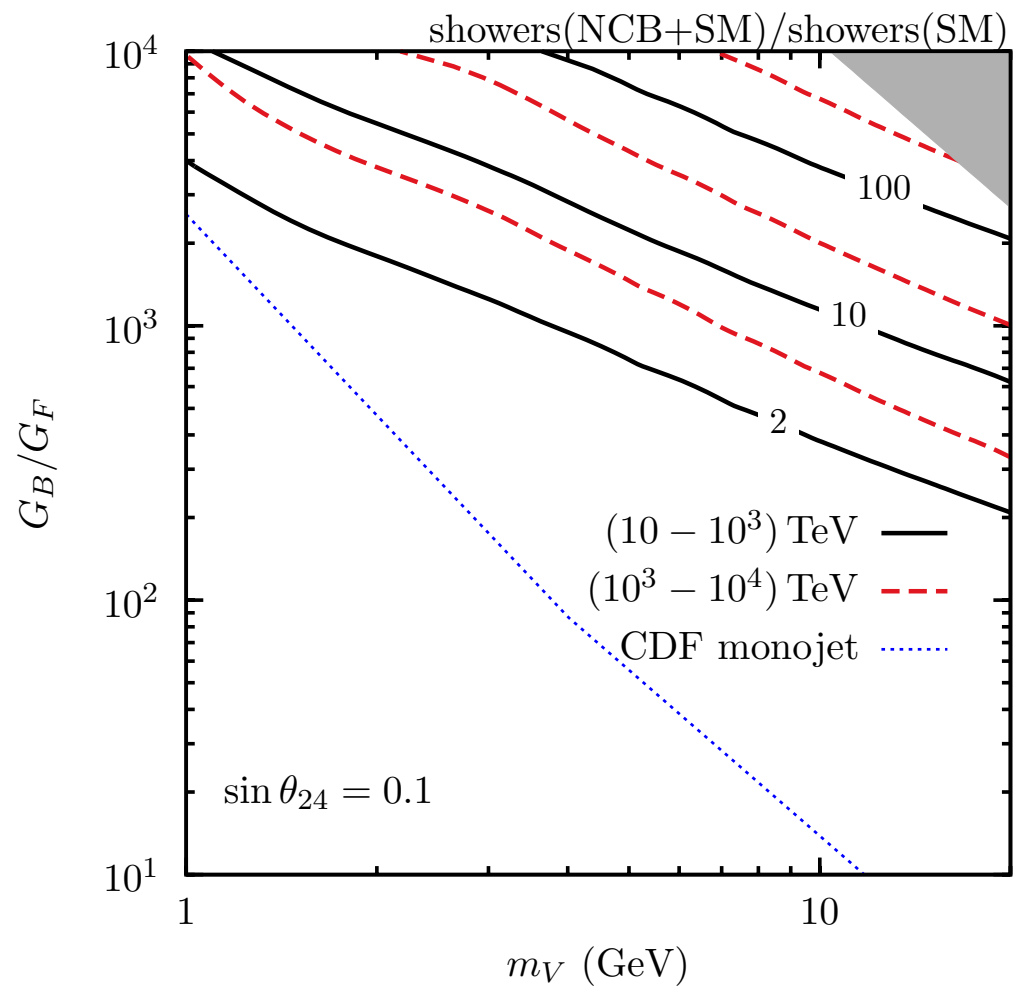
=> we can fix the model by increasing the energy deposition in the scattering, e.g.

ν_{b1}

ν_{b1} ν_{b2}

$\bar{\nu}_{b1}\sigma_{\mu\nu}V^{\mu\nu}\nu_{b2}$
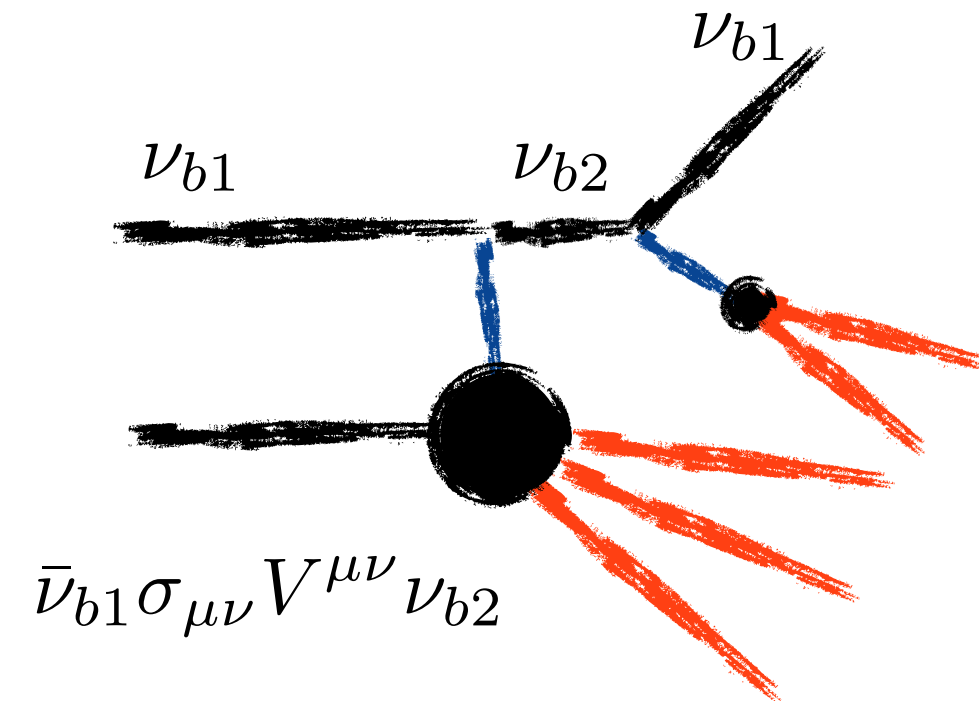
...stay tuned

keV signals from baryonic neutrinos

based on M. Pospelov, JP,
PRD 85, 113016 (2012)

+ updates for 2013

Neutrino oscillation portal

- portal may not guard new interactions on **astrophysical baselines**

$$L_{\mathrm{osc}} = \frac{4\pi E_\nu}{\Delta m^2} \approx 1\,\mathrm{kpc}\left(\frac{10^{-10}\,\mathrm{eV}^2}{\Delta m^2}\right)\left(\frac{E_\nu}{1\,\mathrm{PeV}}\right)$$

consider low energy process

$$L_{\mathrm{osc}} = \frac{4\pi E_\nu}{\Delta m^2} \approx 1\,\mathrm{AU}\left(\frac{10^{-10}\,\mathrm{eV}^2}{\Delta m^2}\right)\left(\frac{E_\nu}{10\,\mathrm{MeV}}\right)$$

- appearance of ν_b in the solar neutrino flux

- NC-type interactions from a solar flux on baryons at MeV energies!

MeV-energy observables from a solar flux of ν_b

- **crucial insight:**

$$\frac{\sigma_{\nu_b N}(\text{elastic})}{\sigma_{\nu_b N}(\text{inelastic})} \sim \frac{A^2}{E_\nu^4 R_N^4} \sim \mathcal{O}(10^8)$$ M. Pospelov PRD 2011

=> Dark Matter searches become competitive with neutrino experiments

=> D breakup in SNO does not constrain this scenario

- Coherent neutrino nucleus scattering with $G_F^2(N/2)^2 \Rightarrow G_B^2 A^2$

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{8\pi}G_F^2 E_\nu^2 \left[Z(4\sin^2\theta_W - 1) + N\right]^2 (1 + \cos\theta)$$

one species

***

three signals?

- **DAMA**: 250 kg of scintillating NaI crystals, running since 1995, exposure in excess of 1 ton x year, no discrimination

- **CoGeNT**: 440 g Ge crystal, 807 live days; ionization only, no discrimination

- **CRESST**: scintillation and phonons; 730 kg days, multi-target

one species

***

four signals?

- **DAMA**: 250 kg of scintillating NaI crystals, running since 1995, exposure in excess of 1 ton x year, no discrimination

- **CoGeNT**: 440 g Ge crystal, 807 live days; ionization only, no discrimination

- **CRESST**: scintillation and phonons; 730 kg days, multi-target

- **CDMS-Si**: ionization and phonons; 140 kg days

one species

***

four signals?
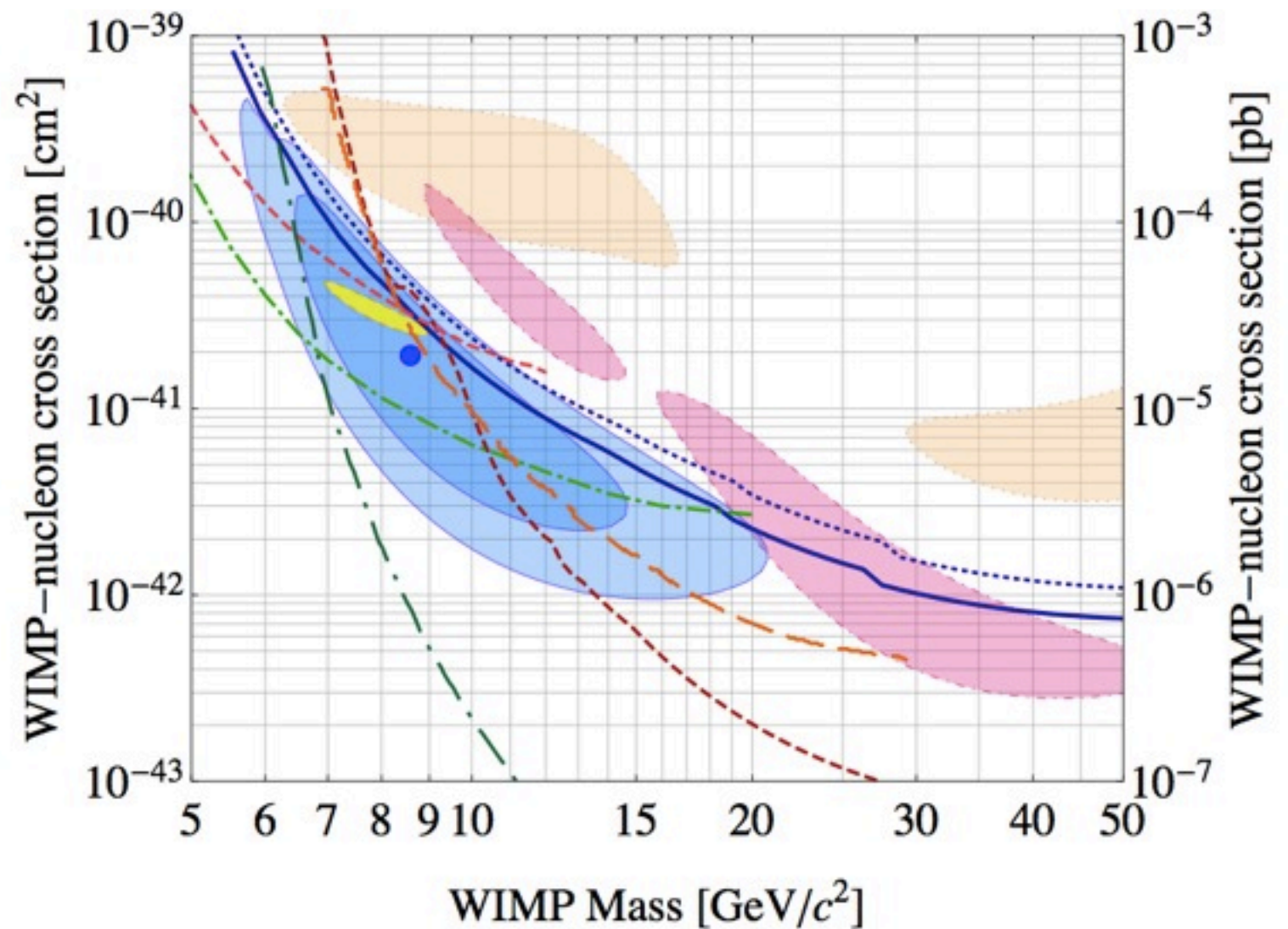
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- **CDMS-Si**: ionization and phonons; 140 kg days

Direct detection of ν_b

like SM-neutrinos with $G_F^2(N/2)^2 \rightarrow G_B^2 A^2$

$$\frac{dR(t)}{dE_R} = N_T \left[\frac{L_0}{L(t)}\right]^2 \sum_i \Phi_i \int_{E_\nu^{\min}} dE_\nu \frac{df_i}{dE_\nu} \frac{d\sigma}{dE_R} P_b(t, E_\nu)$$

appearance probability

overall flux
modulation

average over
neutrino spectrum i

$$L(t) = L_0 \left\{1 - \epsilon \cos\left[\frac{2\pi(t - t_0)}{1\,\mathrm{yr}}\right]\right\}$$

$L_0 = 1\,\mathrm{AU}$

$t_0 \simeq 3\,\mathrm{Jan}\ \ (\mathrm{perihelion})$

$\epsilon = 0.0167\ \ (\mathrm{eccentricity})$

Direct detection of ν_b

$A_{\mathrm{Ge}} = 70 - 76$
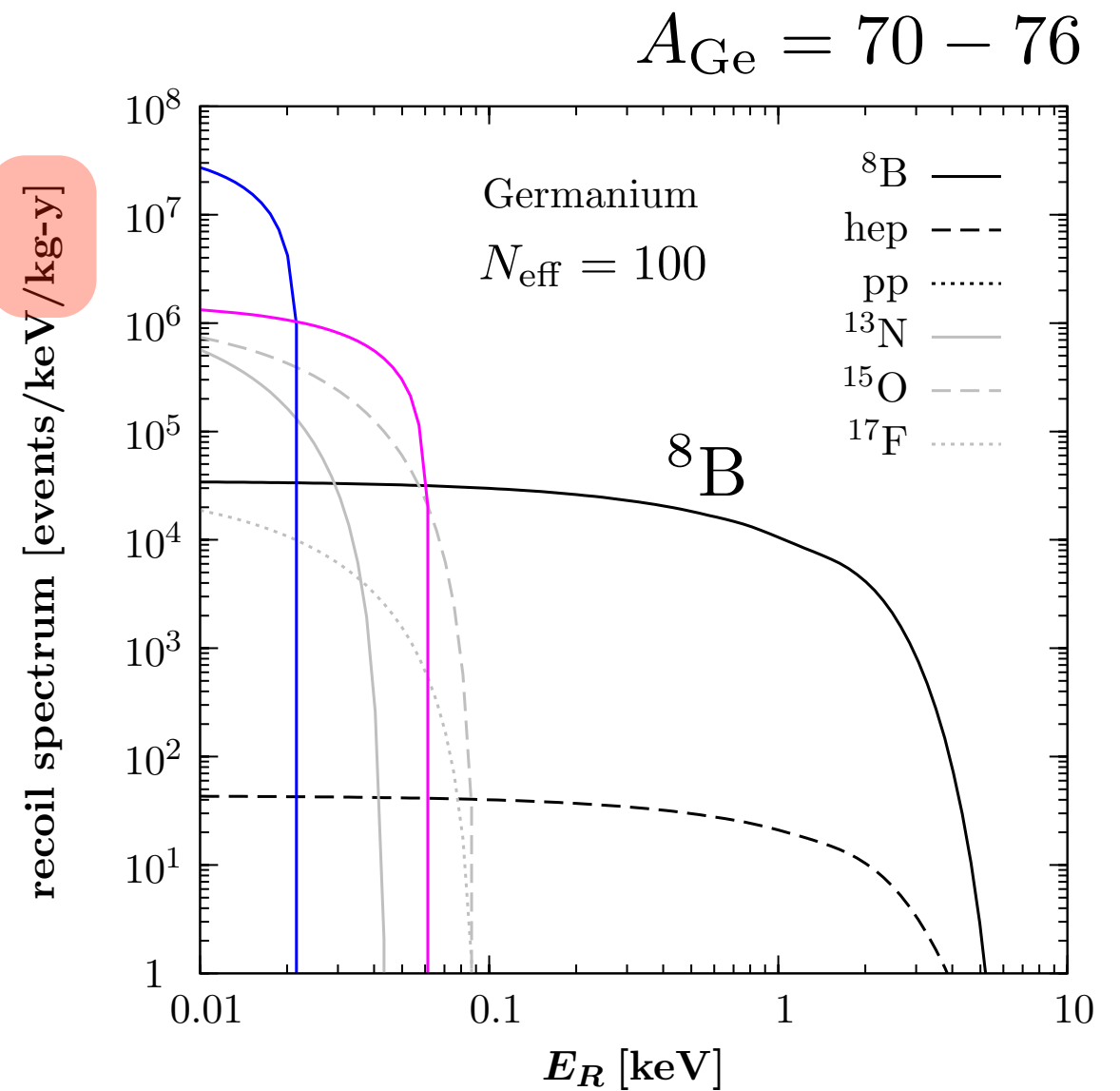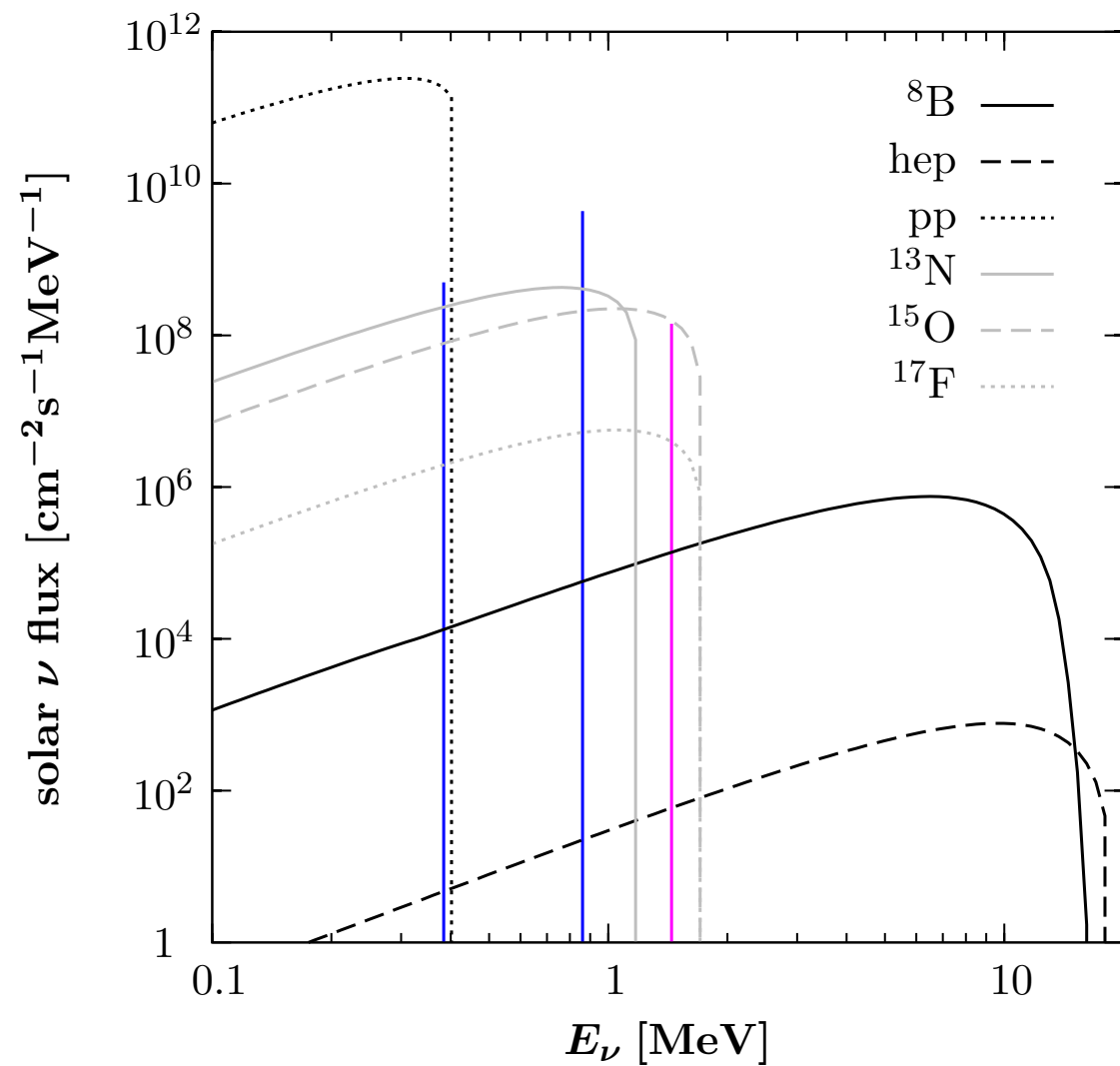
$$P_{eb}(L, E_\nu) \simeq \sin^2(2\theta_{24}) \sin^2\left[\frac{\Delta m L(t)}{4 E_\nu}\right]$$

$$\mathcal{N}_{\mathrm{eff}}^2 = \frac{1}{2}\left(\frac{G_B}{G_F}\right)^2 \sin^2 2\theta_{24}$$

high energy solar flux exits sun mainly as ν_2

Direct detection of ν_b

more modulation here

$$\frac{dR(t)}{dE_R} = N_T \left[\frac{L_0}{L(t)} \right]^2 \sum_i \Phi_i \int_{E_\nu^{\min}} dE_\nu \, \frac{df_i}{dE_\nu} \frac{d\sigma}{dE_R} P_b(t, E_\nu)$$

$$\frac{L_{\rm osc}}{L_0} \simeq 0.5 \times \left(\frac{10^{-10}\,{\rm eV}}{\Delta m^2} \right) \left(\frac{E_\nu}{10\,{\rm MeV}} \right) \qquad \text{oscillation-length on the order sun-earth distance}$$

=> **flip phase** for high energy part of the neutrino spectrum? **explain DAMA**?

DAMA

modulation amplitude

DAMA

time series

DAMA/LIBRA 0.87 ton×yr

residuals (cpd/kg/keV)

(2–4 keV)

(2–5 keV)

(2–6 keV)

days since Jan 1, 1995
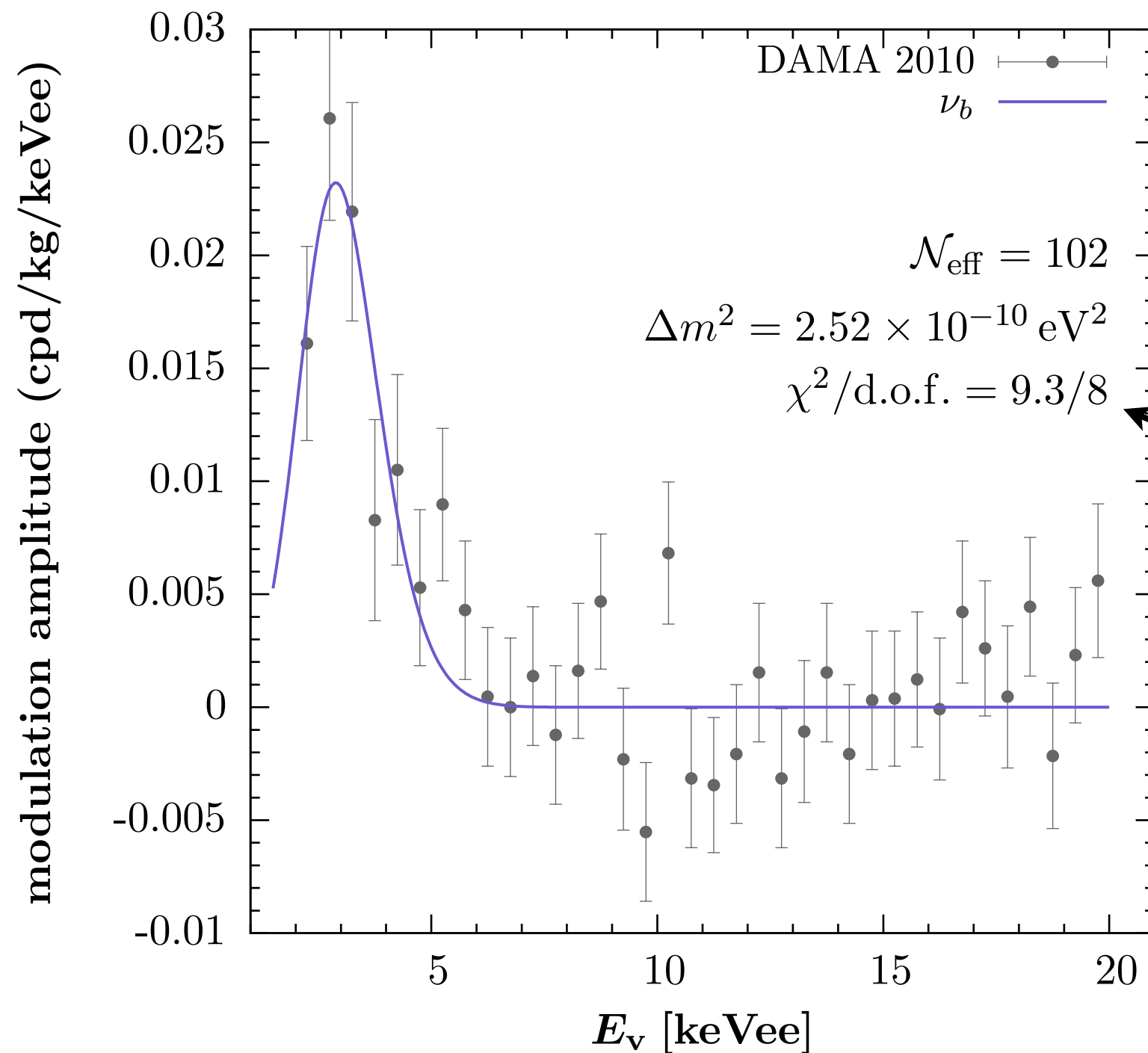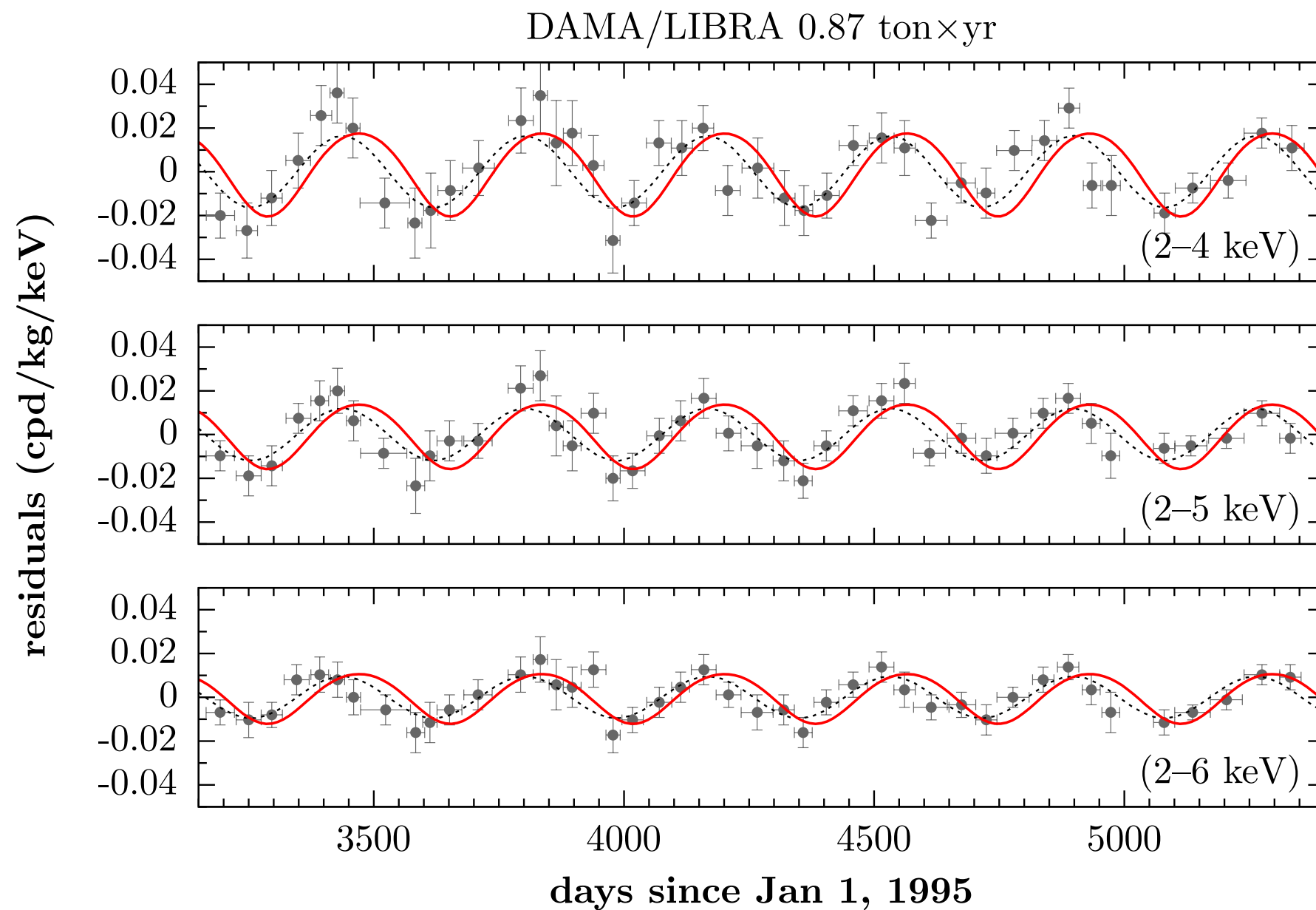
phase off by one month!

CoGeNT

- unexplained rise in Ge towards threshold
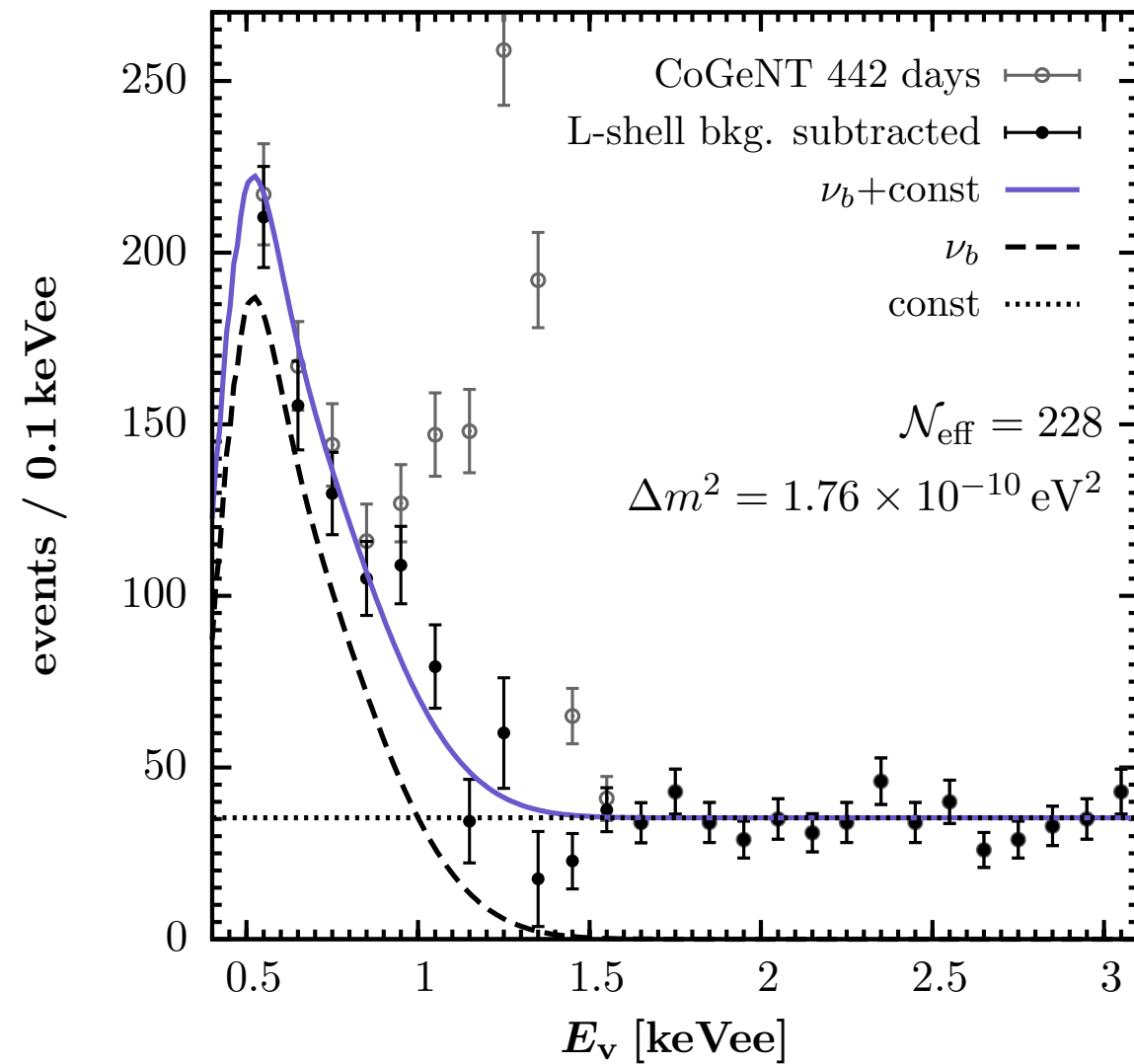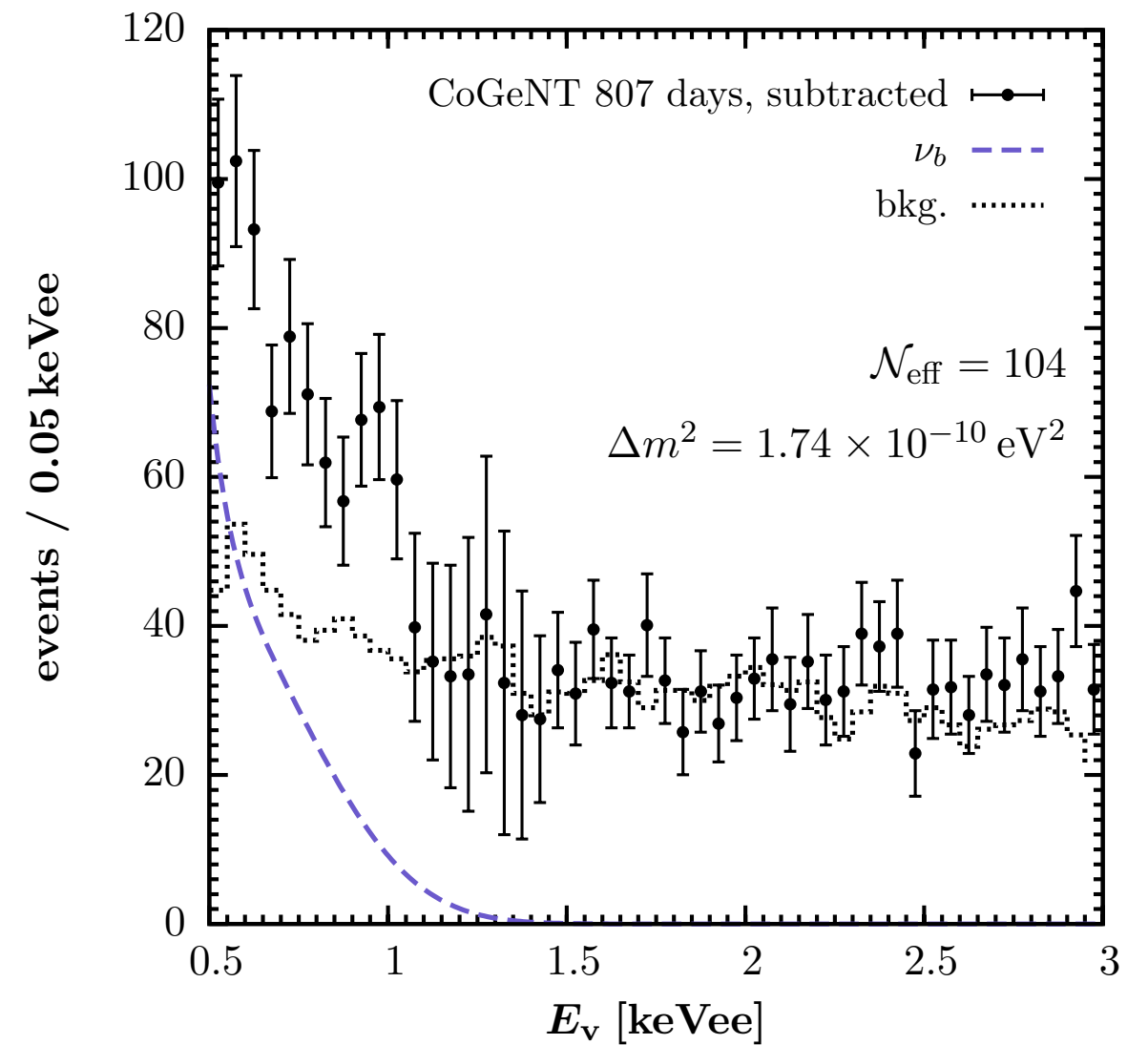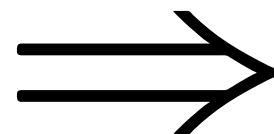
2012 ⟹ 2013

CRESST-II

Angloher et al EPJC 2012

CRESST-II 730 kg×days

counts/keV

ν_b
e^-/γ
Pb
α
n
observed

E_v (keV)
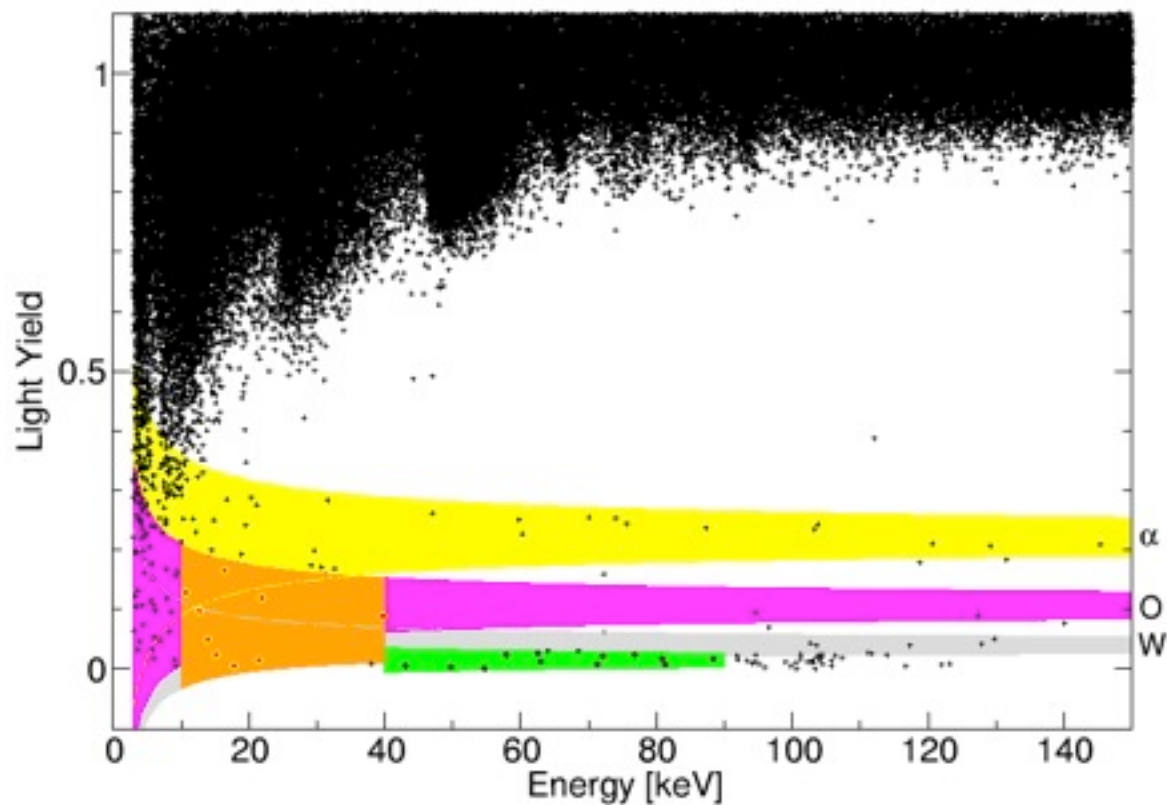
- 8 CaWO$_4$ crystals, 730kg days

- 67 events, only half understood as background
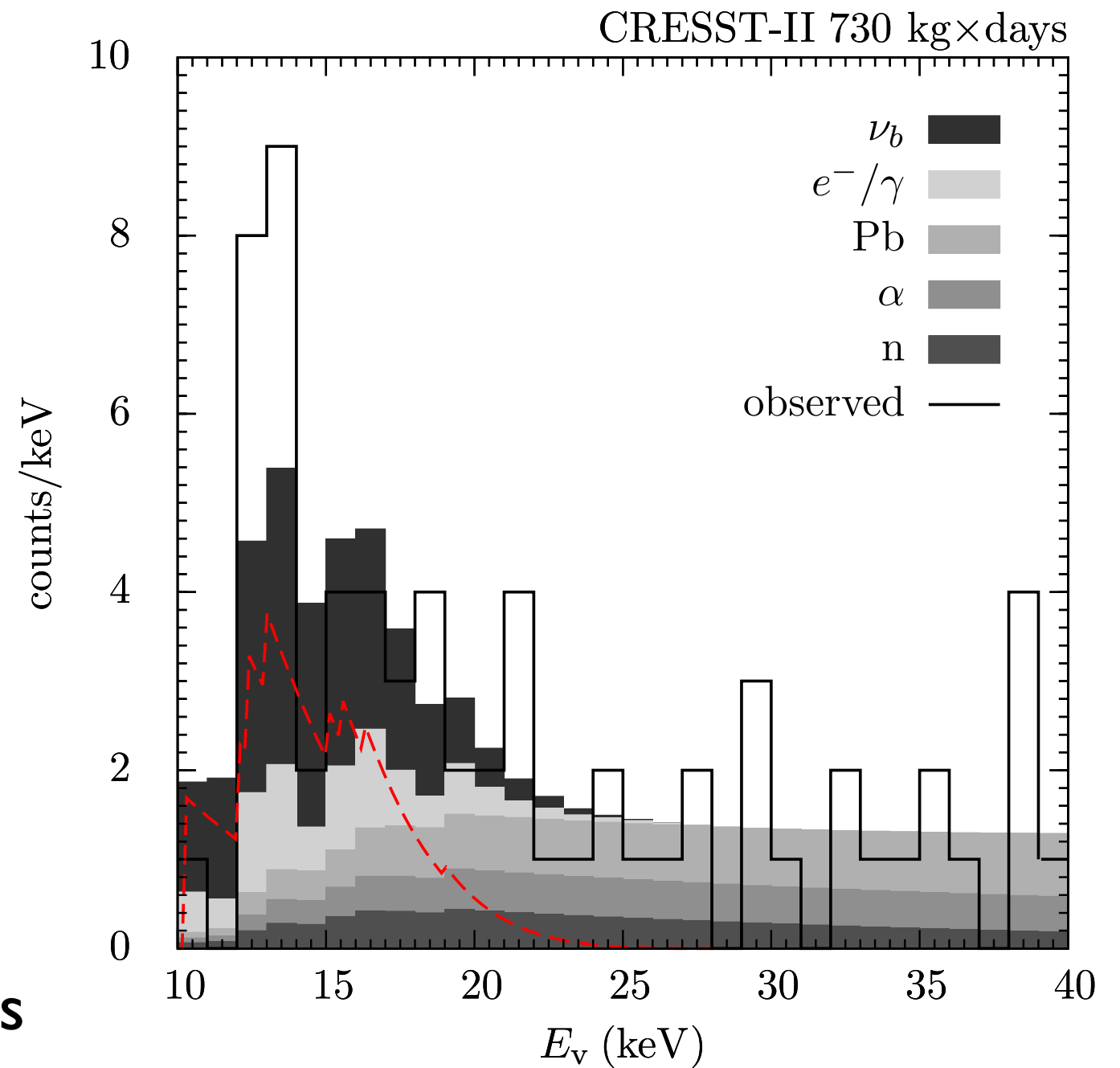
$\chi^2_P/\text{d.o.f.} = 27.8/28$

CDMS-Si 2013

3 events, 0.2% probability of *known background-only* hypothesis

CDMS-II Si 140 kg×days

$\Delta m^2 = 4 \times 10^{-9} \text{ eV}^2$

$\mathcal{N}_{\text{eff}} = 49$

2012

$\mathcal{N}_{\mathrm{eff}}$

99% C.L.

Δm^2 [eV^2]

CRESST-II
CoGeNT
DAMA
CoGeNT hull

Josef Pradler - INFO 2013

2013

$\mathcal{N}_{\mathrm{eff}}$

Δm^2 [eV²]

99% C.L.

CDMS-II Si
CRESST-II
CoGeNT
DAMA

2013

$\mathcal{N}_{\text{eff}}$

100

10

10^{-10} 10^{-9}

Δm^2 [eV^2]

99% C.L.
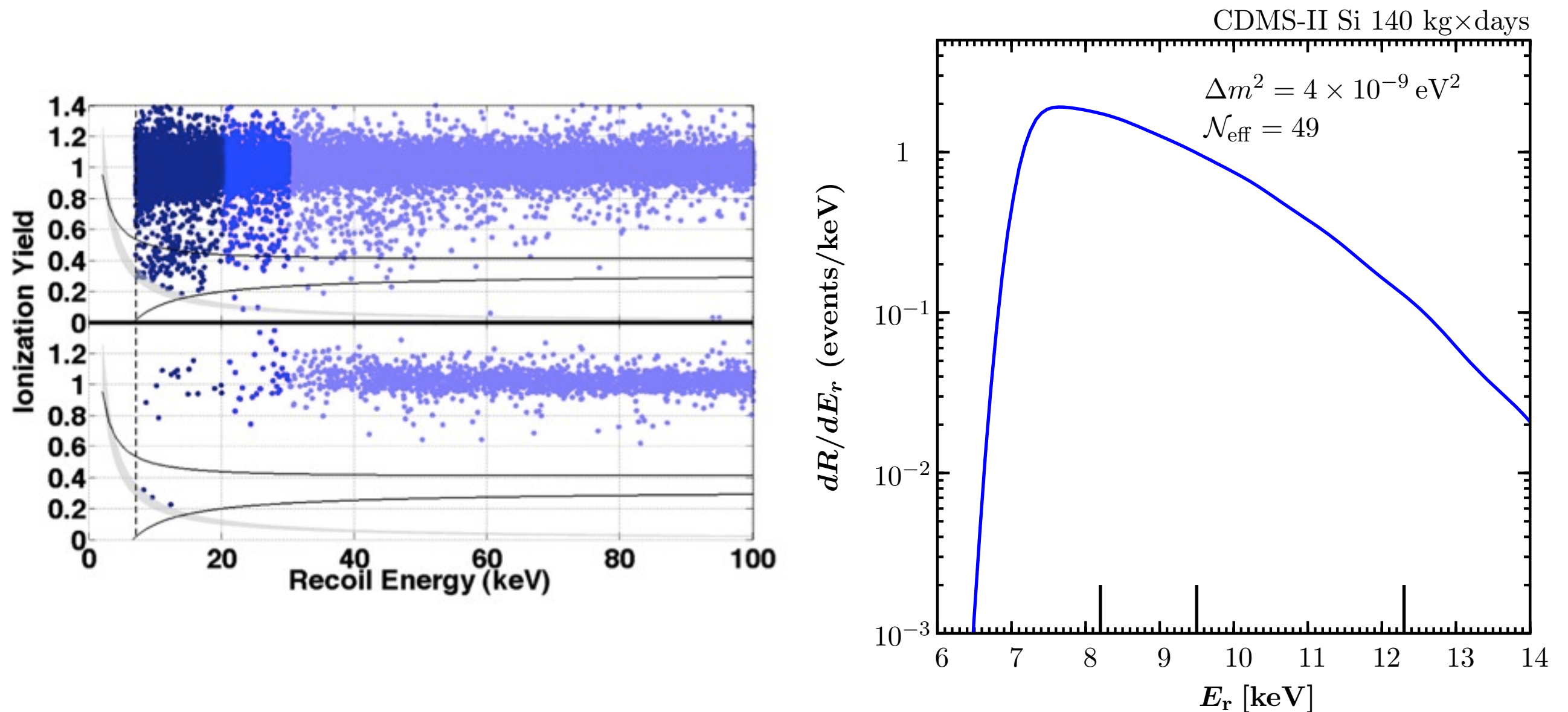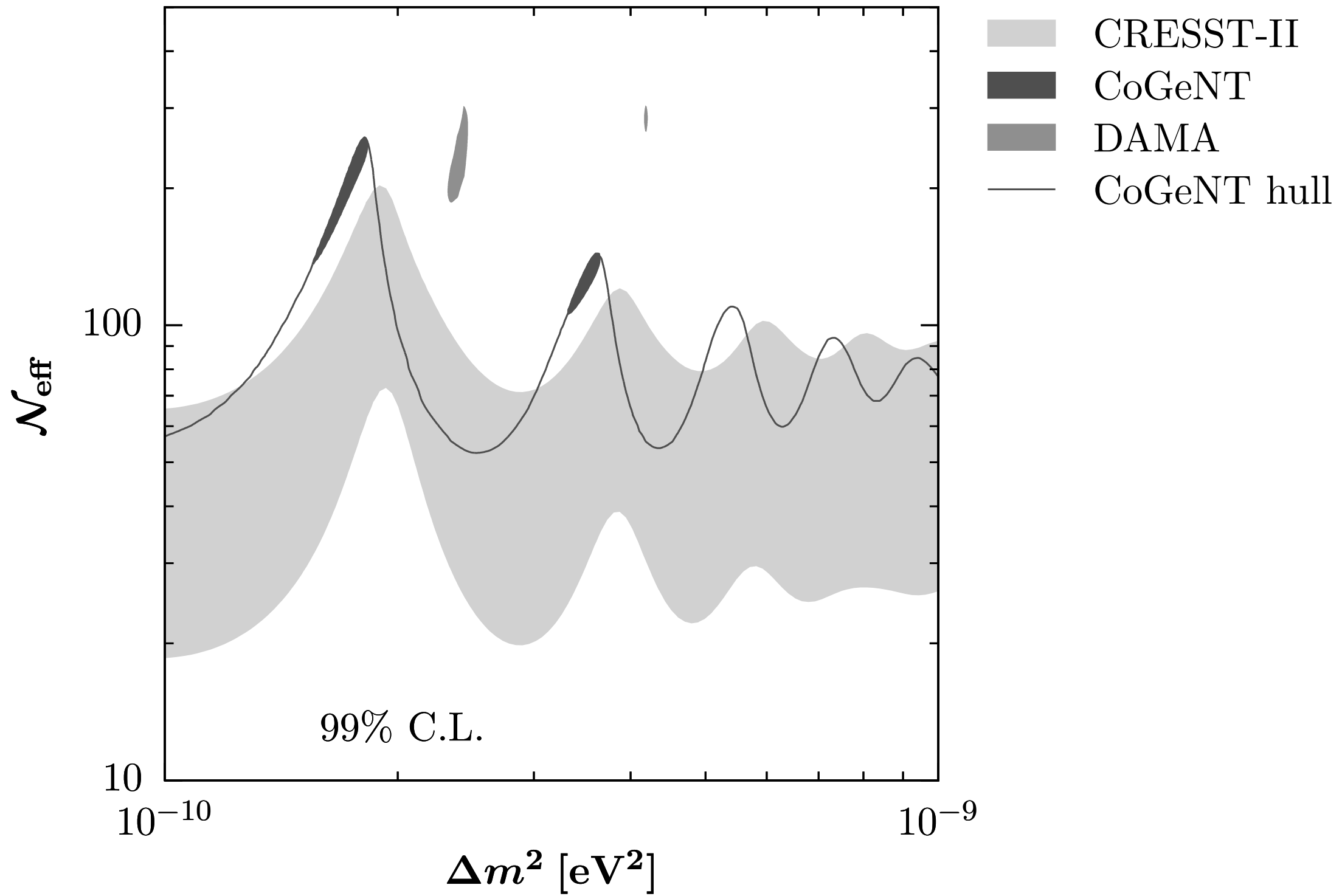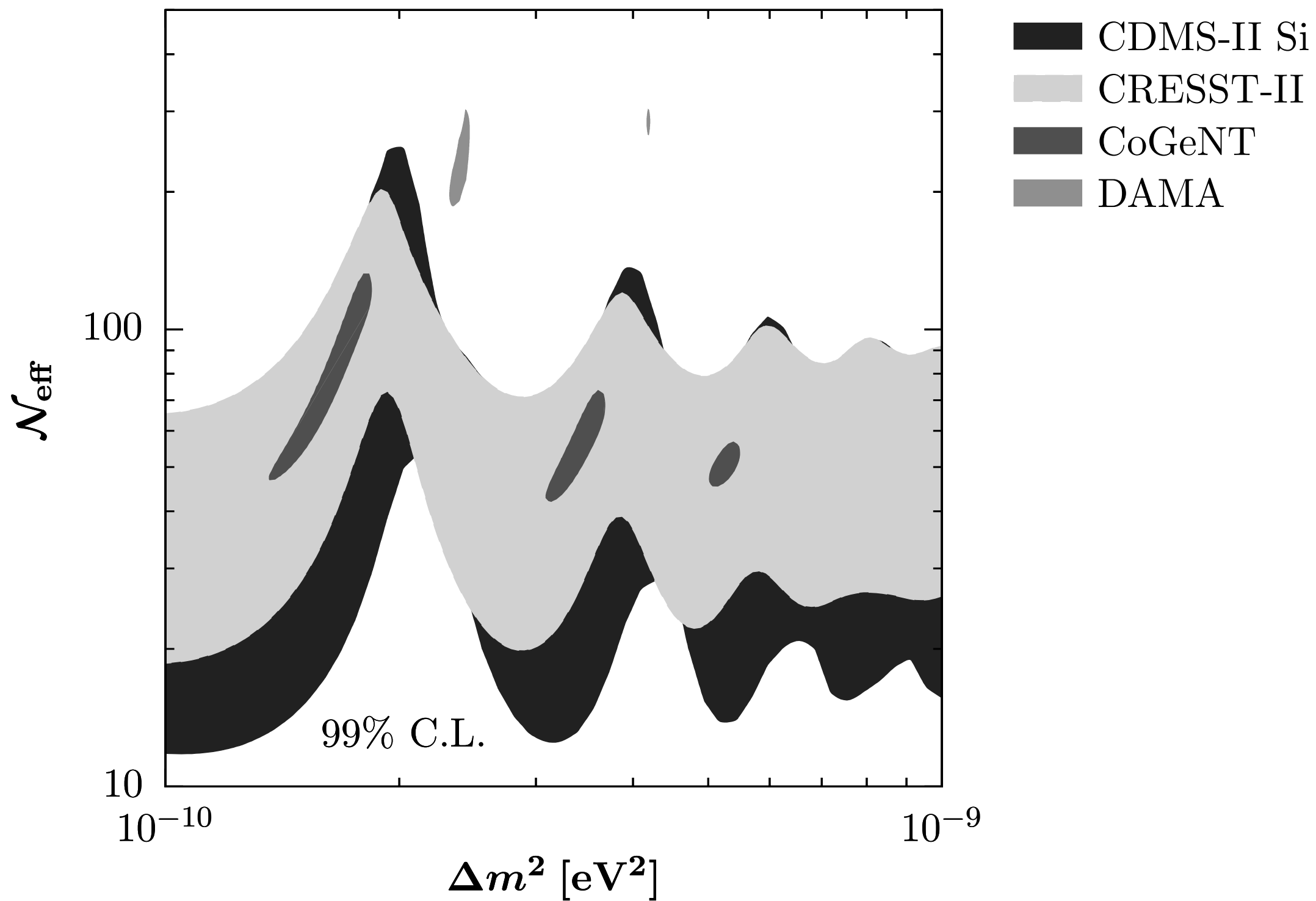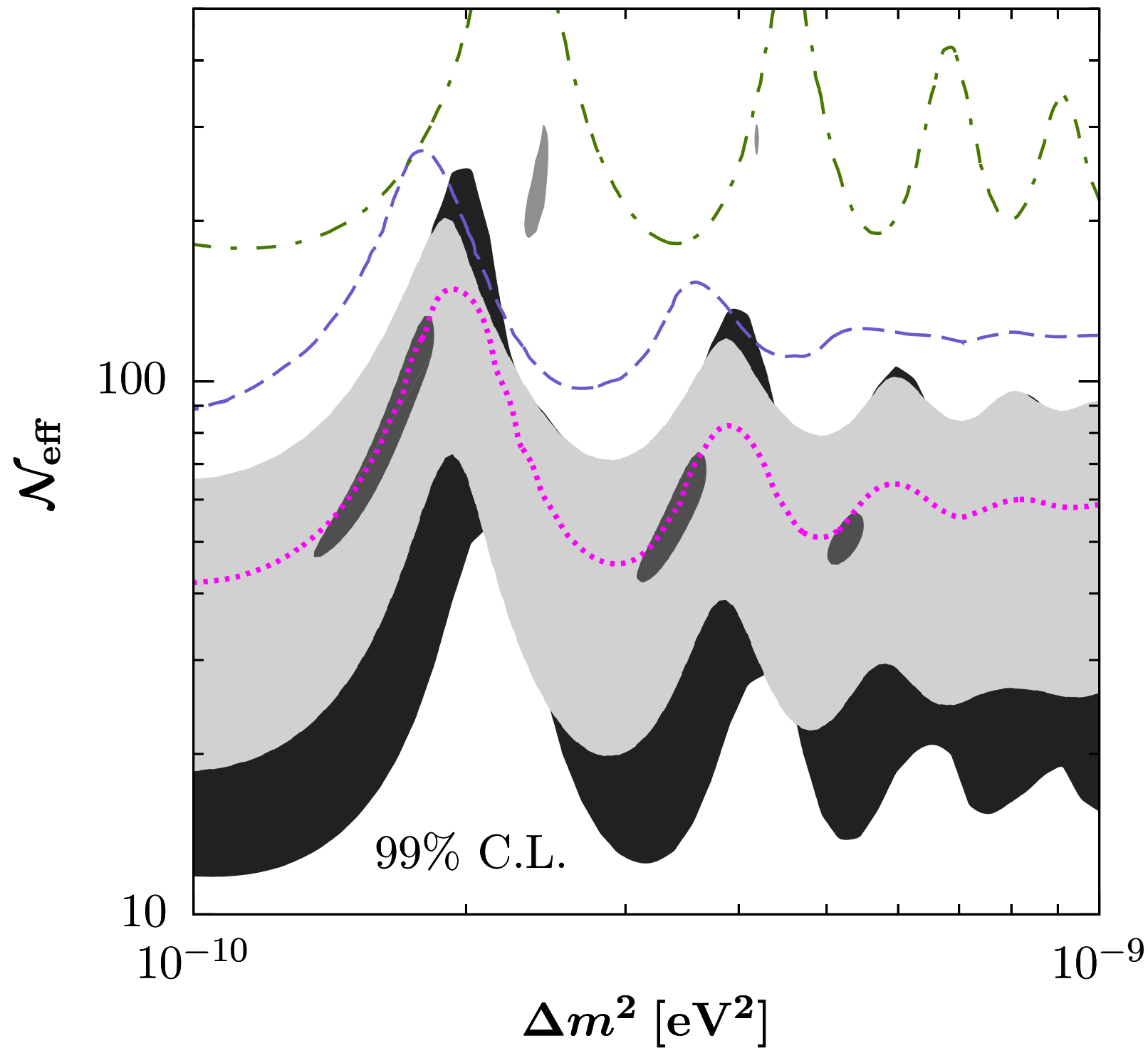
CDMS-II Si

CRESST-II

CoGeNT

DAMA

CDMS-II low th.

Xenon100 (100d)

Xenon10 low th.

uncertain, because of poorly known nuclear recoil energy calibration;
here Qy from Angle et. al 2011 (Xe10)

Josef Pradler - INFO 2013

Outlook
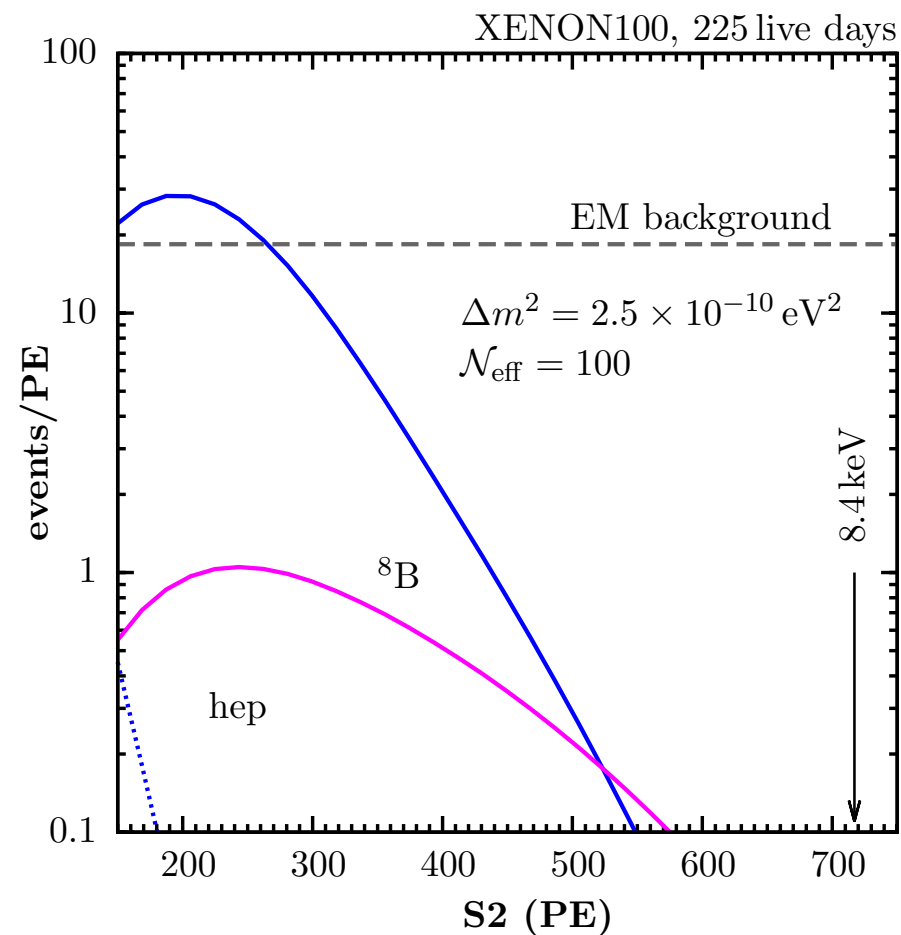
prediction for Xenon100 (using most recent Qy measurement by Xe100, Aprile et al. 2013)
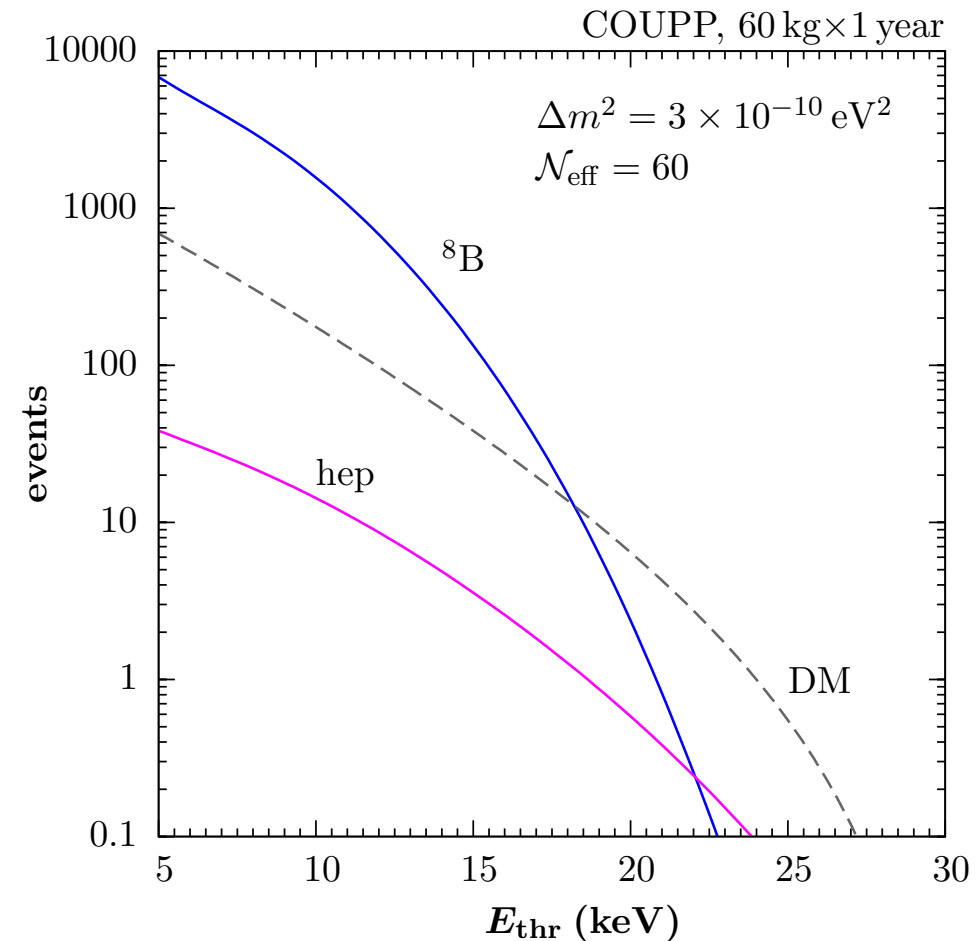
prediction for COUPP bubble chamber (CF$_3$I)

- Borexino plans to constrain the model from ^{12}C*$(4.4\,\mathrm{MeV})$ possibly down to $\mathcal{N}_{\mathrm{eff}} = 10$

Baryonic neutrinos in SN

freezes out quickly
=> high T spectrum!
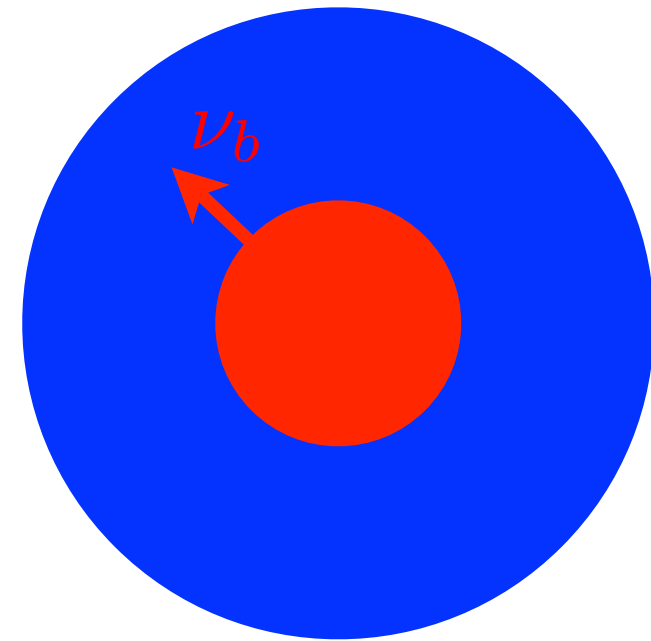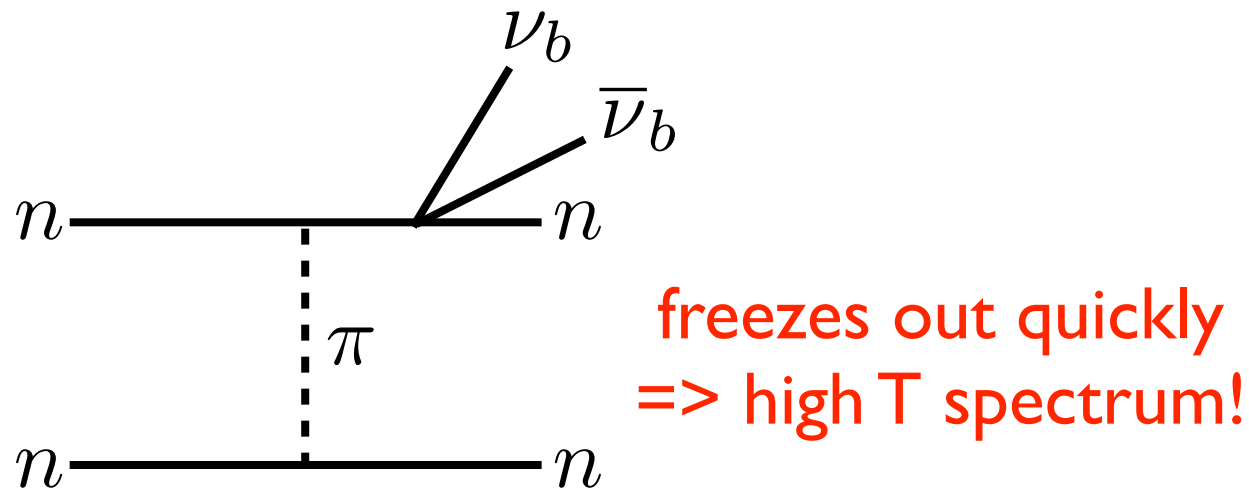
highly insulating scattering sphere

- nearby SN detectable => signal in direct detection from oscillation

- Efficient trapping with large diffusion zone will likely prevent direct emission of ν_b with high enough temperature for direct detection

- can it affect dynamics of explosions?

- diffuse SN signal may be detectable as well

MeV signals
from dark matter

WIMP miracle

from Feng 2008

direct detection

relic abundance
indirect detection

collider

DM   DM

SM   SM
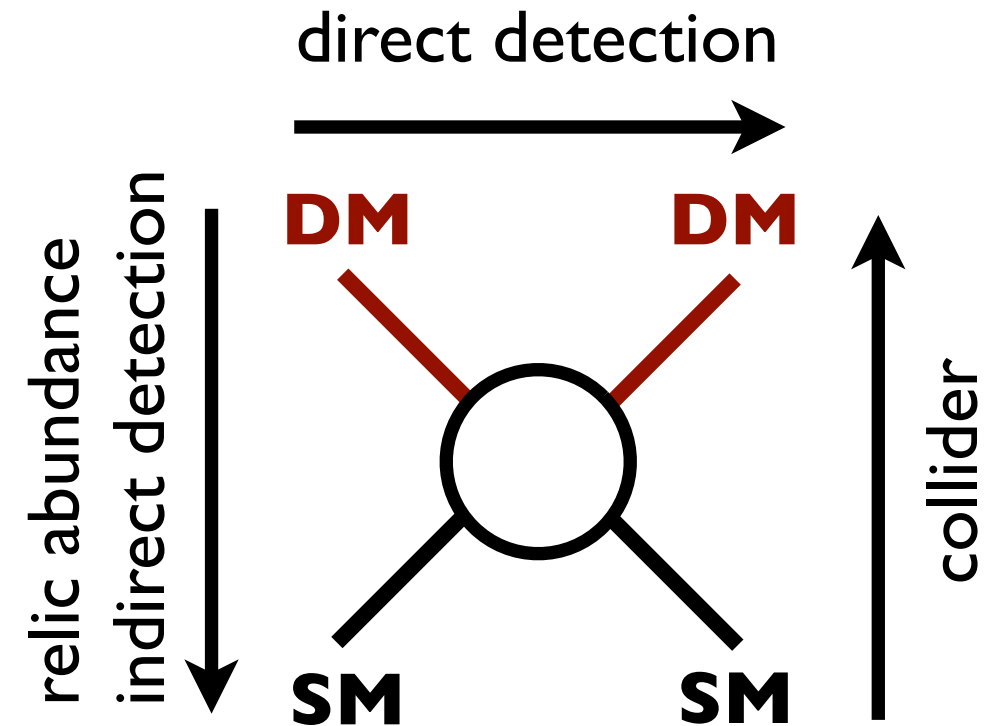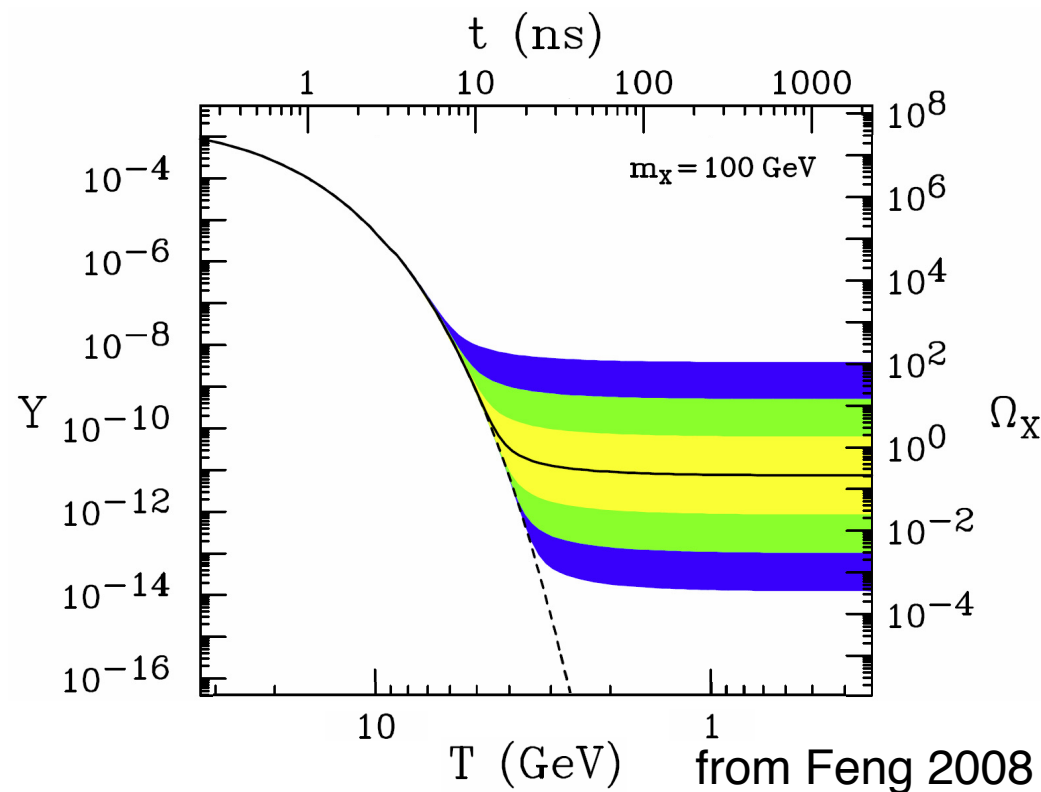
imposing a thermal history can provide an important calibration point for mass and interaction strengths of DM

$$\Omega_{\mathrm{DM}} \propto \frac{1}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

$$\sigma_v v \sim \frac{\alpha_{\mathrm{DM}}^2}{m_{DM}} \sim 1\,\mathrm{pb}$$

=> electroweak scale physics with weak strength interactions offer a natural solution = "WIMP"

but there many more possibilities: superWIMPs, secluded WIMPs, super-cold DM...

=> fuels hopes for a laboratory test

cheat-sheet for a WIMP miracle

- What if direct link to SM is too feeble?

  => no correct thermal abundance

  => little direct detection prospects
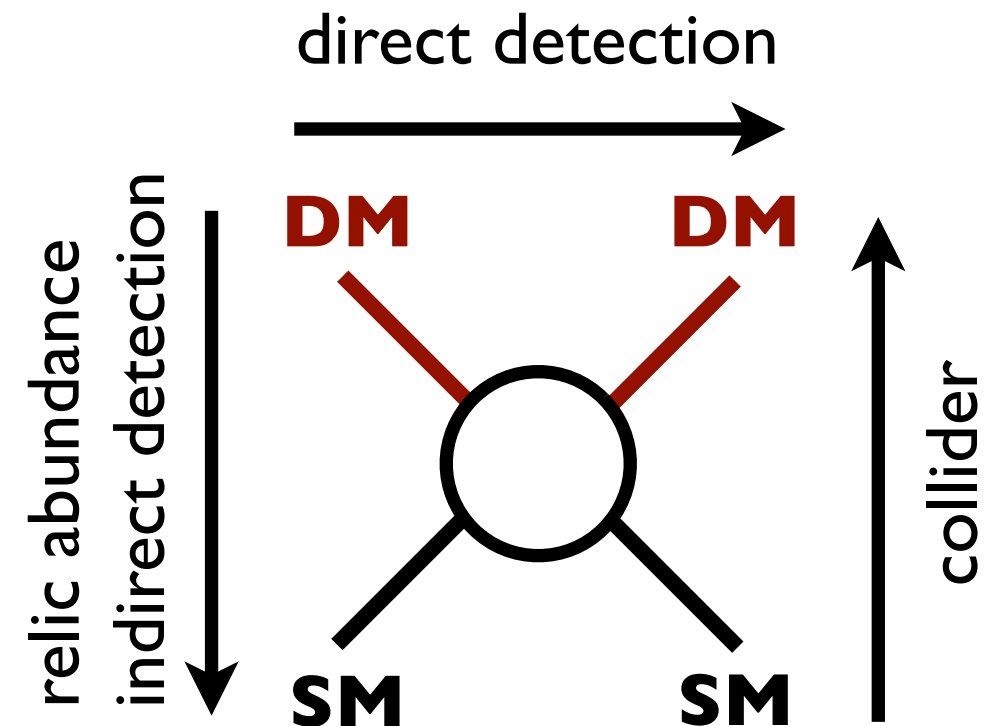
- Co-annihilation can guarantee abundance   Griest, Seckel PRD 1991

$$X^0 X^\pm \to SM$$
$$X^0 X^0 \to X^+ X^- \to SM$$
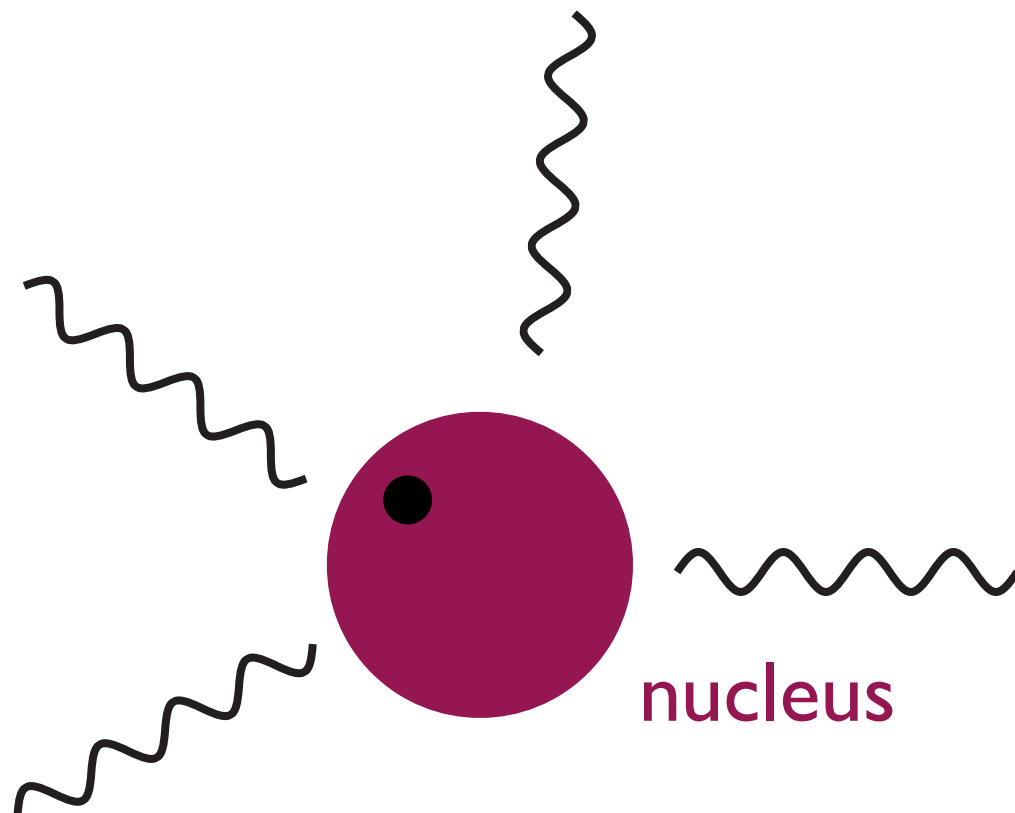$$T_{\text{freeze}} \simeq \frac{m_{X^0}}{20} \Rightarrow \Delta m \lesssim 0.05 m_{X^0}$$
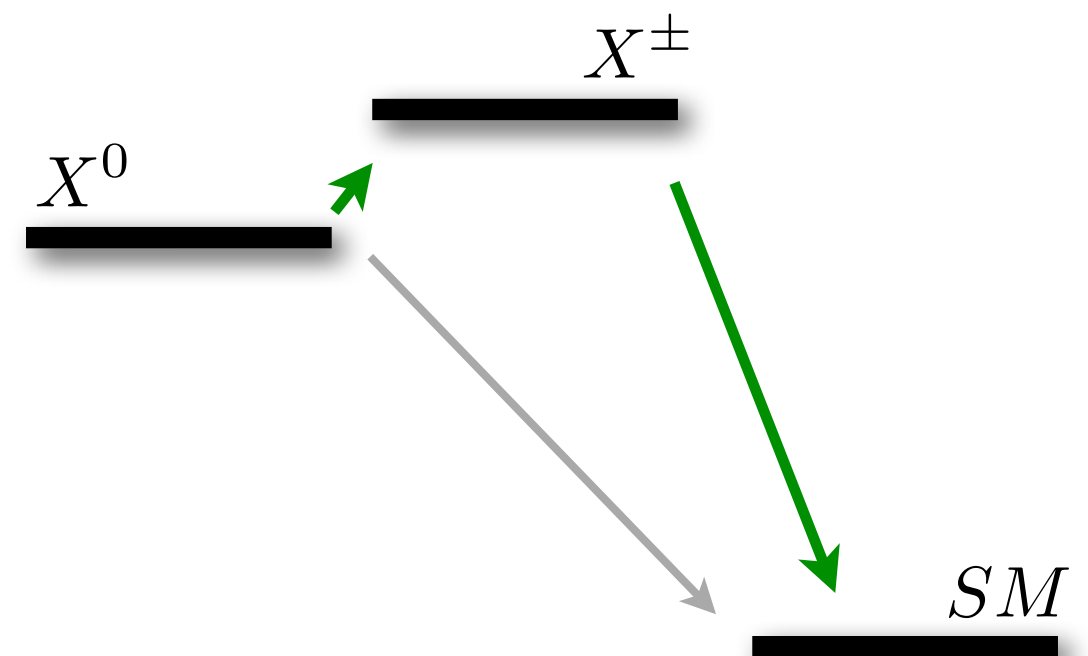
Excited states of DM

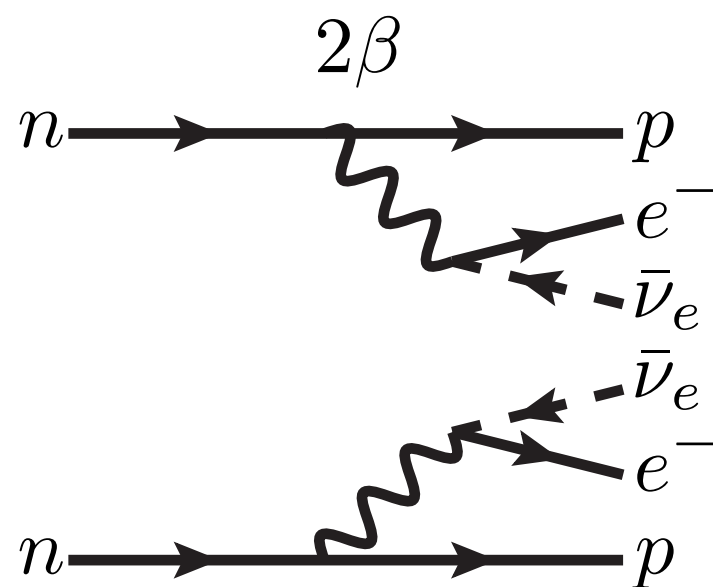- in the potential of the nucleus, excited state is accessible

=> capture $E_b = \mathcal{O}(\mathrm{MeV})$

$$V(r_b) + \Delta m < 0$$

"critical zone"

X^0
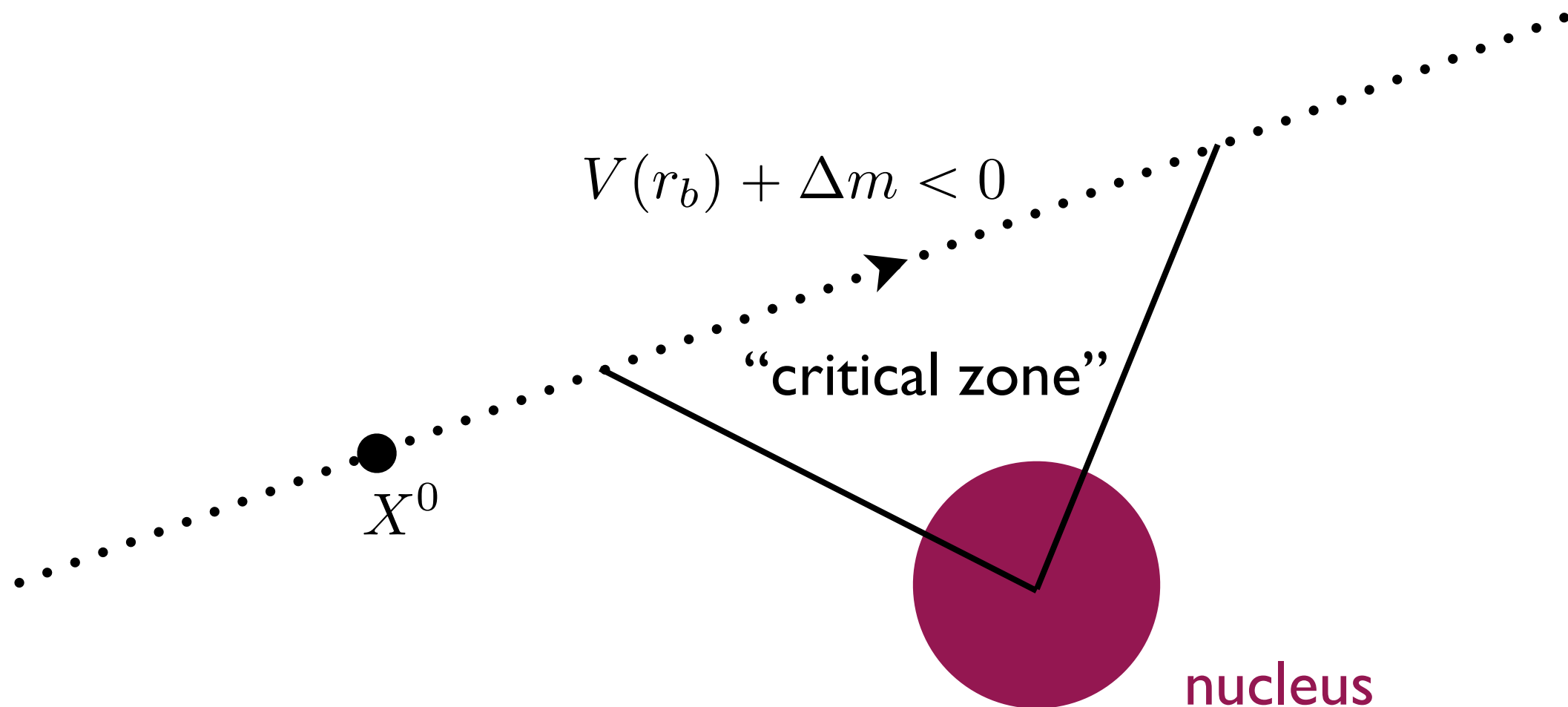
nucleus

Excited states of DM

- in the potential of the nucleus, excited state is accessible

  => capture $E_b = \mathcal{O}(\mathrm{MeV})$
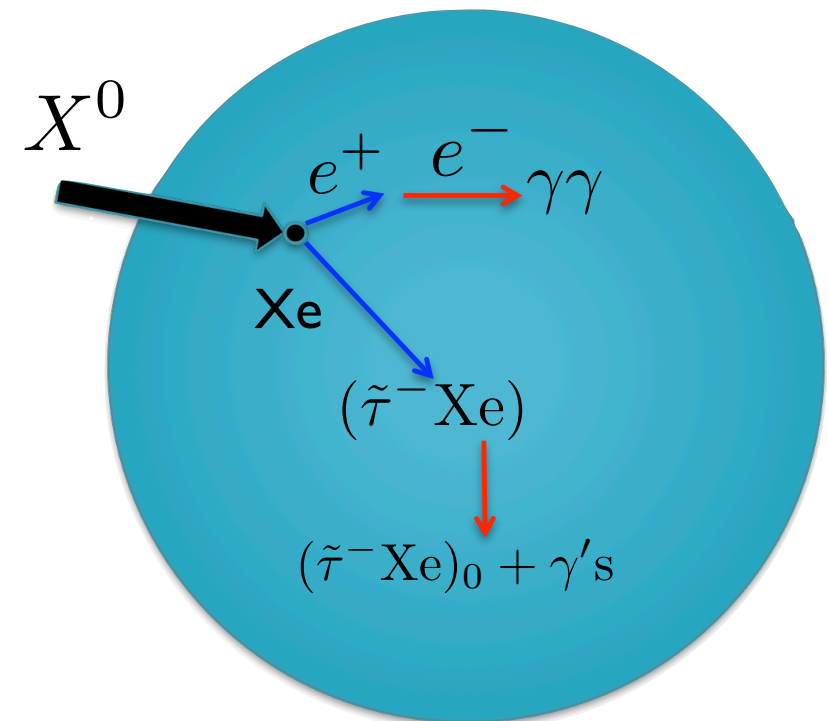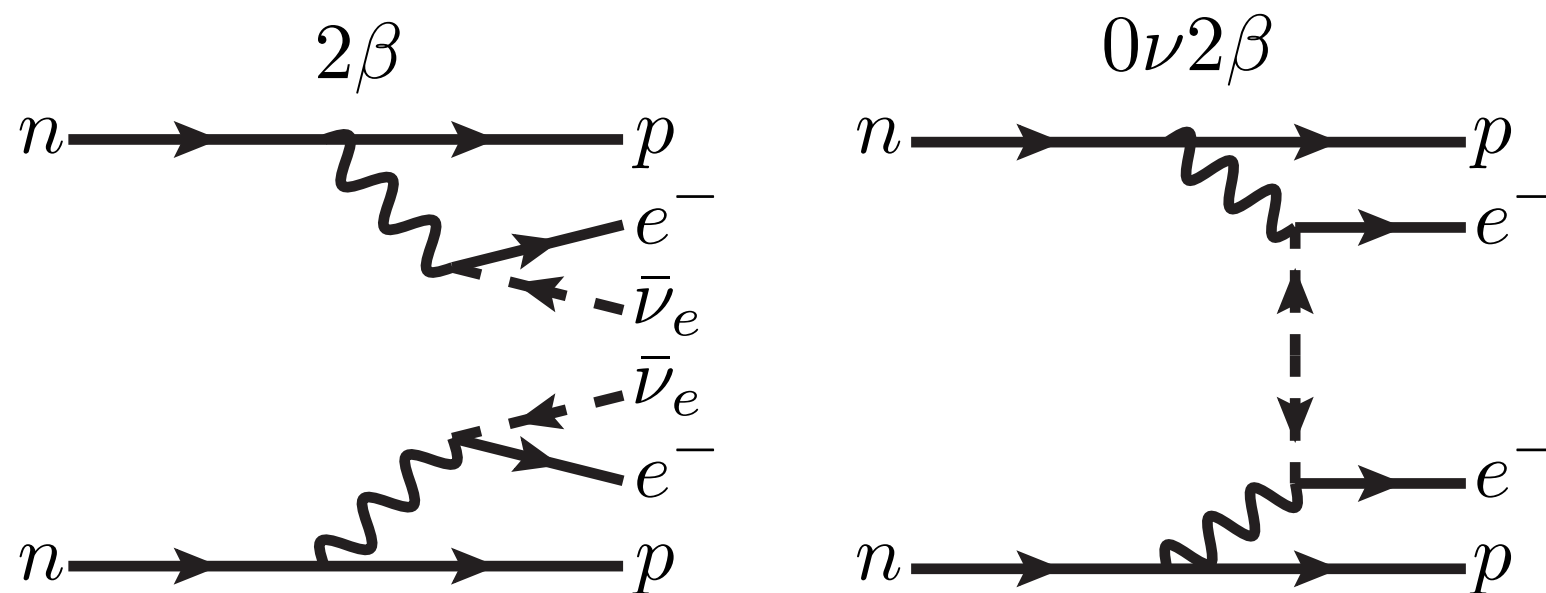
- offers a new kind of signature

nucleus

DM in neutrino experiments

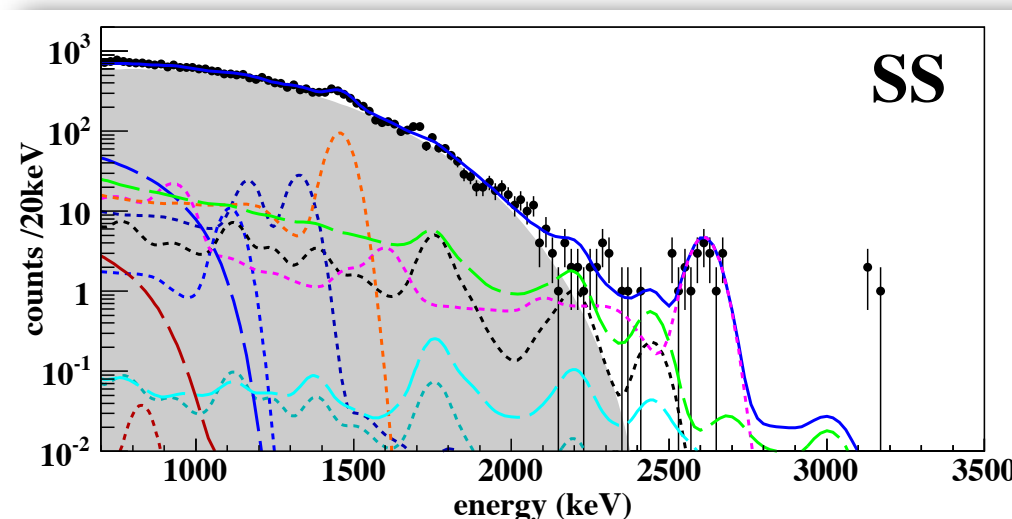- $0\nu2\beta$ experiments look for extremely rare MeV energy deposits
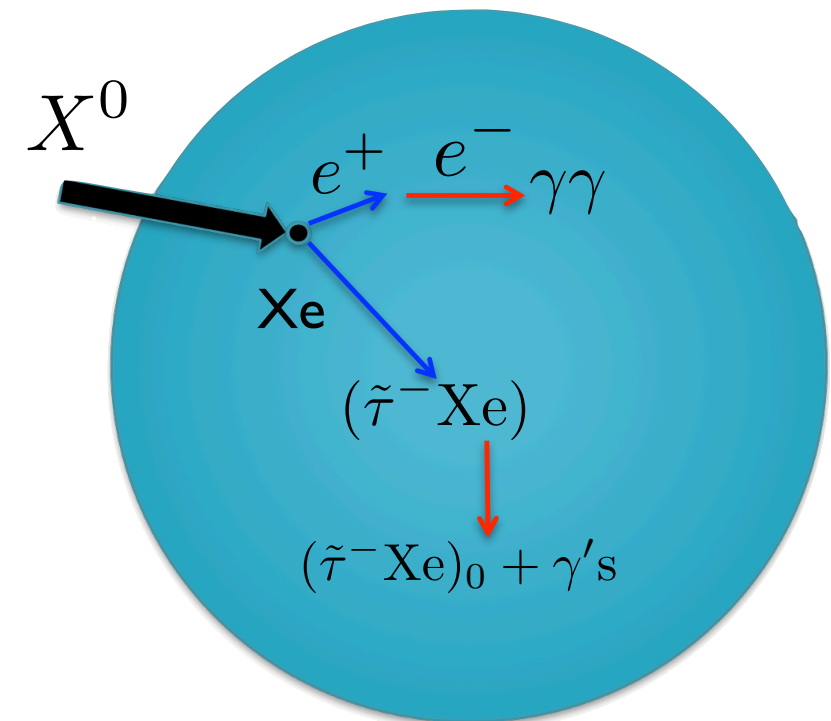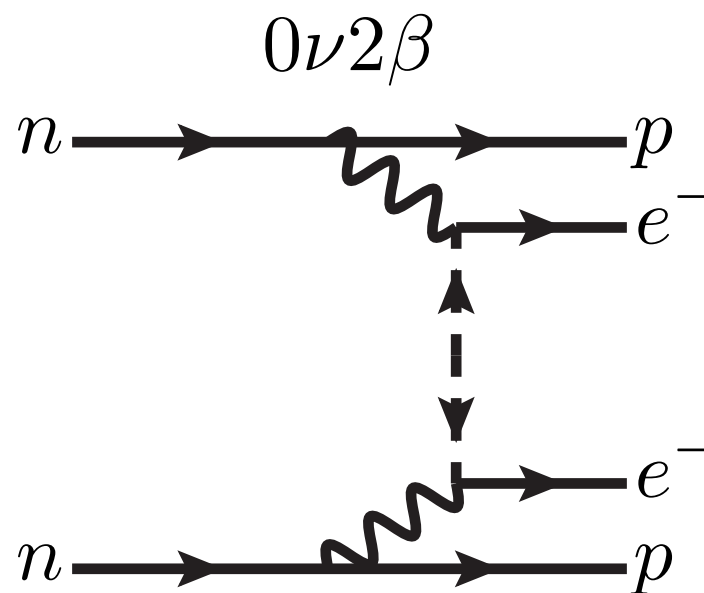
DM in neutrino experiments

- $0\nu2\beta$ experiments look for extremely rare MeV energy deposits
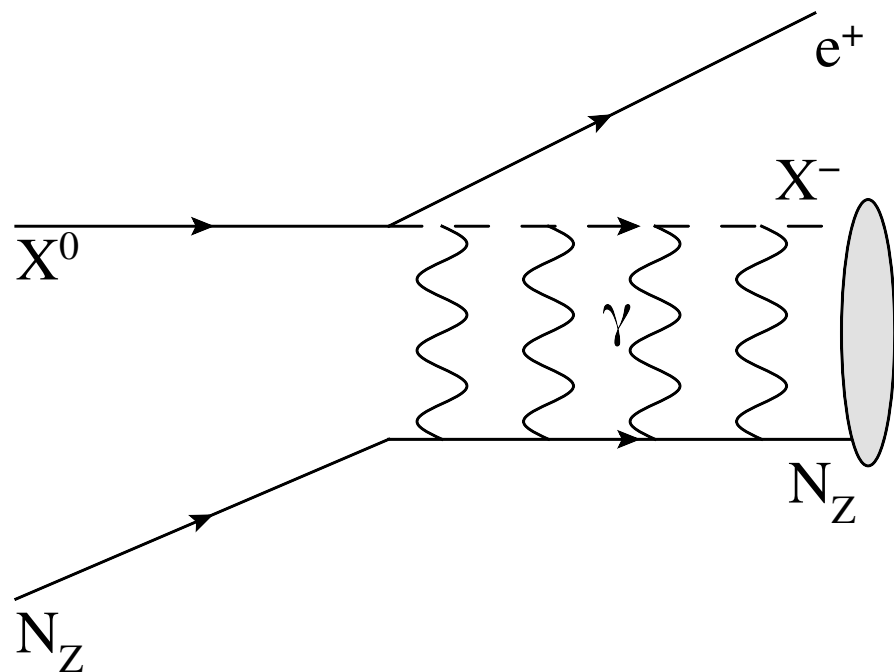

- first data from EXO-200 and Kamland-Zen

EXO-200 collaboration, 2012

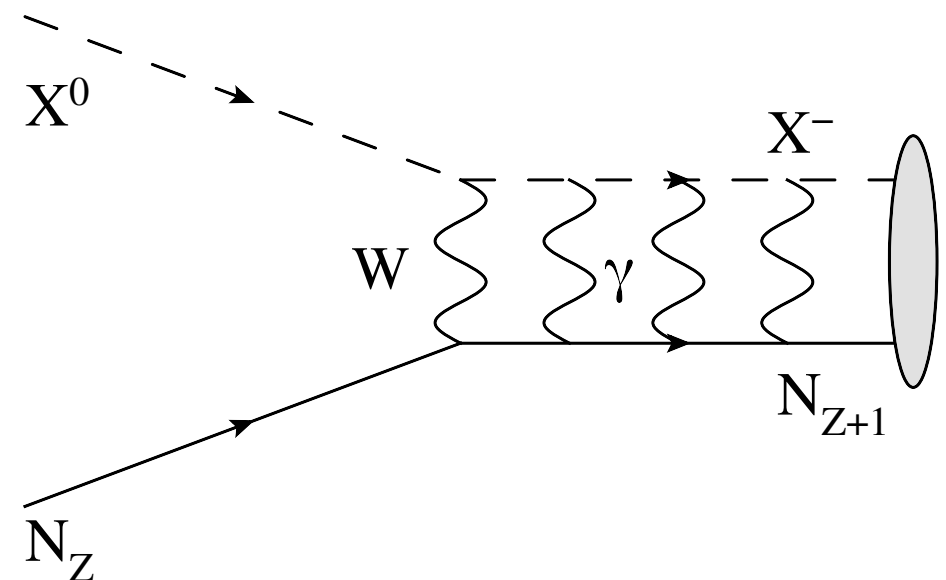# Generic cases for charged excitations

Case A: different spin

$$\mathcal{L} \supset y X^0 e^+ X^- + h.c.$$

$$N_Z + X^0 \rightarrow (N_Z X^-) + e^+$$

Case B: same spin

$$\mathcal{L} \supset g_{\text{eff}}(X^0 \partial^\mu X^+ - X^+ \partial^\mu X^0) W^-_\mu$$

$$N_Z + X^0 \rightarrow (N_{Z+1} X^-)$$

Readily realized in
Supersymmetry

Case A: different spin

$$\mathcal{L} \supset y X^0 e^+ X^- + h.c.$$

$$\downarrow$$

$$\mathcal{L}_{\mathrm{A}} = \bar{\chi}(g_{eL}\mathbb{P}_L + g_{eR}\mathbb{P}_R)e\tilde{\tau}^\dagger + \mathrm{h.c.}$$

$\uparrow$

flavor off-diagonal
Yukawa coupling

"neutralino-stau scenario"

Case B: same spin

$$\mathcal{L} \supset g_{\mathrm{eff}}(X^0 \partial^\mu X^+ - X^+ \partial^\mu X^0)W_\mu^-$$

$$\downarrow$$

$$\mathcal{L}_{\mathrm{B}} = \frac{g_{\mathrm{eff}}}{2}W^{-\mu}(\partial_\mu \tilde{\tau}^\dagger \tilde{\nu}^0 - \tilde{\tau}^\dagger \partial_\mu \tilde{\nu}^0) + \mathrm{h.c.}$$

$$g_{\mathrm{eff}} = g_2 \cos\theta_{\tilde{\tau}} \cos\theta_{\tilde{\nu}^0}$$

$\uparrow \qquad \uparrow$

LR stau mixing angle

sterile-active mixing angle
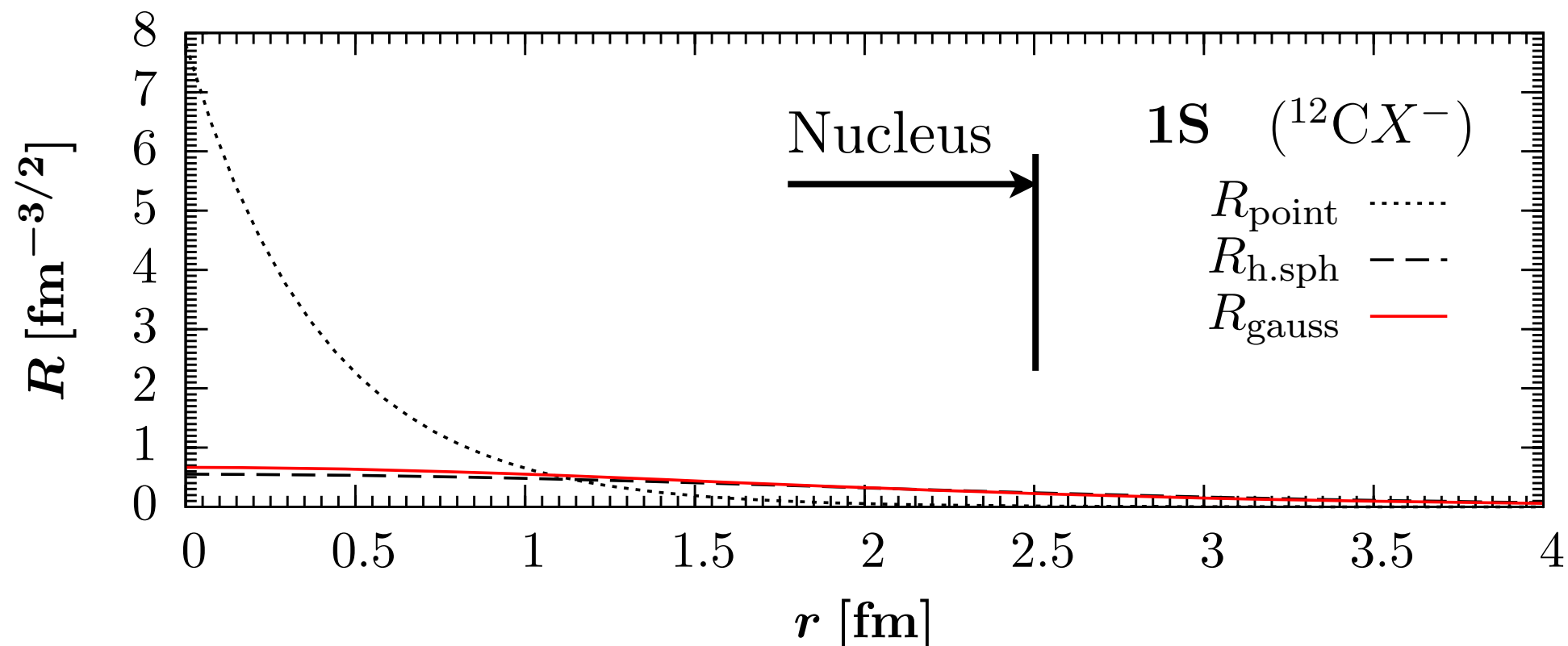
"sneutrino-stau scenario"

Exotic bound states

basic properties

X^-

N

- Ground state wave function for various nuclear charge distributions, e.g. $^{12}\mathrm{C}$

$$|E_b(\mathrm{point})| = 10.7\,\mathrm{MeV}$$

$$|E_b(\mathrm{hom.sph.})| = 2.8\,\mathrm{MeV}$$

$$|E_b(\mathrm{gauss})| = 2.6\,\mathrm{MeV}$$

Nucleus — 1S $\left(^{12}\mathrm{C}X^-\right)$

R_{point} ·······
$R_{\mathrm{h.sph}}$ – – –
R_{gauss} ——

Axes: $R\,[\mathrm{fm}^{-3/2}]$ versus $r\,[\mathrm{fm}]$

Recombination
Case A

- cross section into state n, l

$$\sigma_{nl} v \simeq \frac{|g_{eL}|^2 + |g_{eR}|^2}{8\pi m_\chi} \sqrt{(|E_{b,nl}| - \Delta m)^2 - m_e^2} (|E_{b,nl}| - \Delta m) I_{nl}(v)$$

(F.T. of the wave function)

$$I_{nlm}(v) = \int d^3 r_1 d^3 r_2 \, \psi^*_{nlm}(\mathbf{r_1}) \psi_{nlm}(\mathbf{r_2}) e^{i\mu(\mathbf{r_1} - \mathbf{r_2}) \cdot \mathbf{v}}$$

$$= \delta_{m0}(4\pi)(2l+1) \left[\int dr \, r u_{nl}(r) j_l(\mu r v) \right]^2$$

$\sigma \propto 1/v$ ✓ inelastic cross section ("Bethe's law")

Recombination
Case A

- cross section into state n, l

$$\sigma_{nl} v \simeq \frac{|g_{eL}|^2 + |g_{eR}|^2}{8\pi m_\chi} \sqrt{(|E_{b,nl}| - \Delta m)^2 - m_e^2}(|E_{b,nl}| - \Delta m) I_{nl}(v)$$

↓

kinematic condition:
bound state can only form if
potential energy can overcome
mass gap and create a positron

- total cross section

$$\sigma_A v = \sum_{n,l} \sigma_{n,l} v$$

↓

which n's are accessible depends on Δm
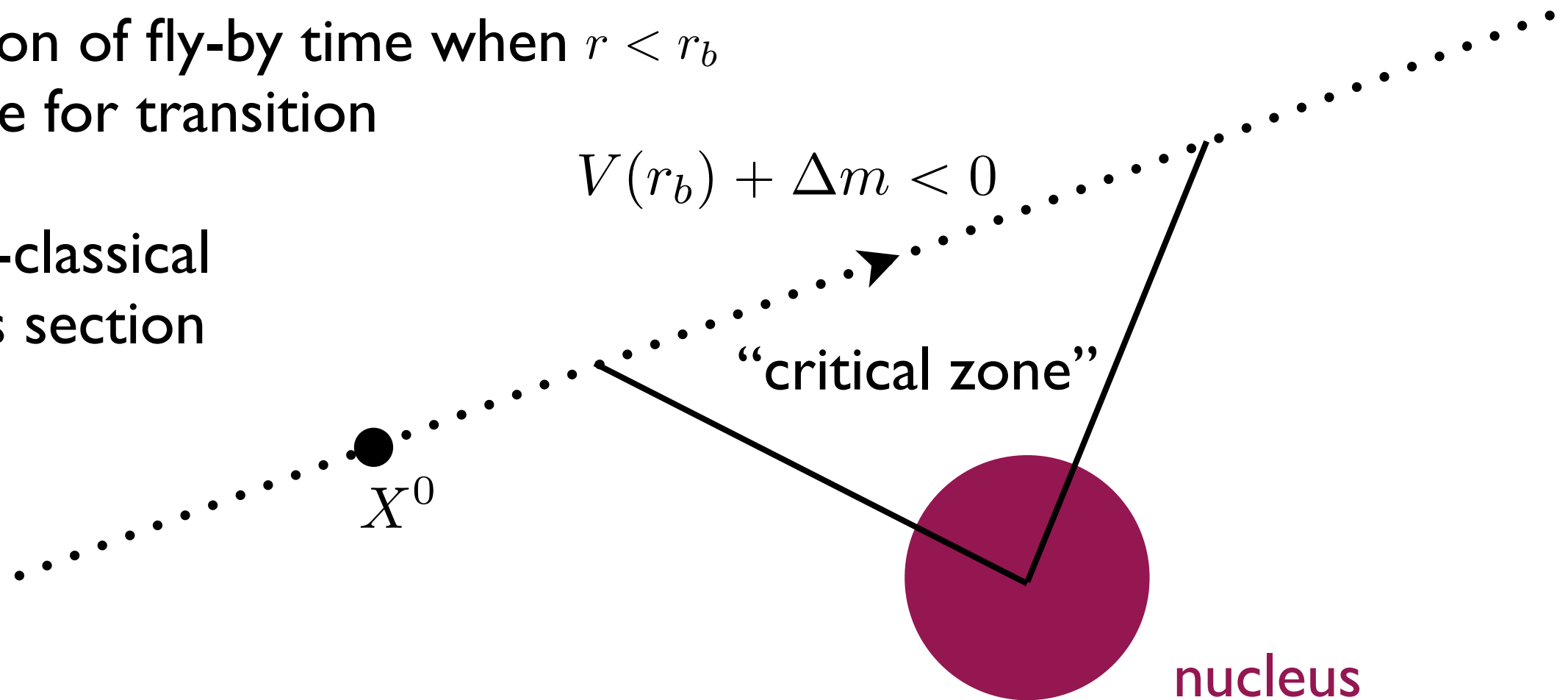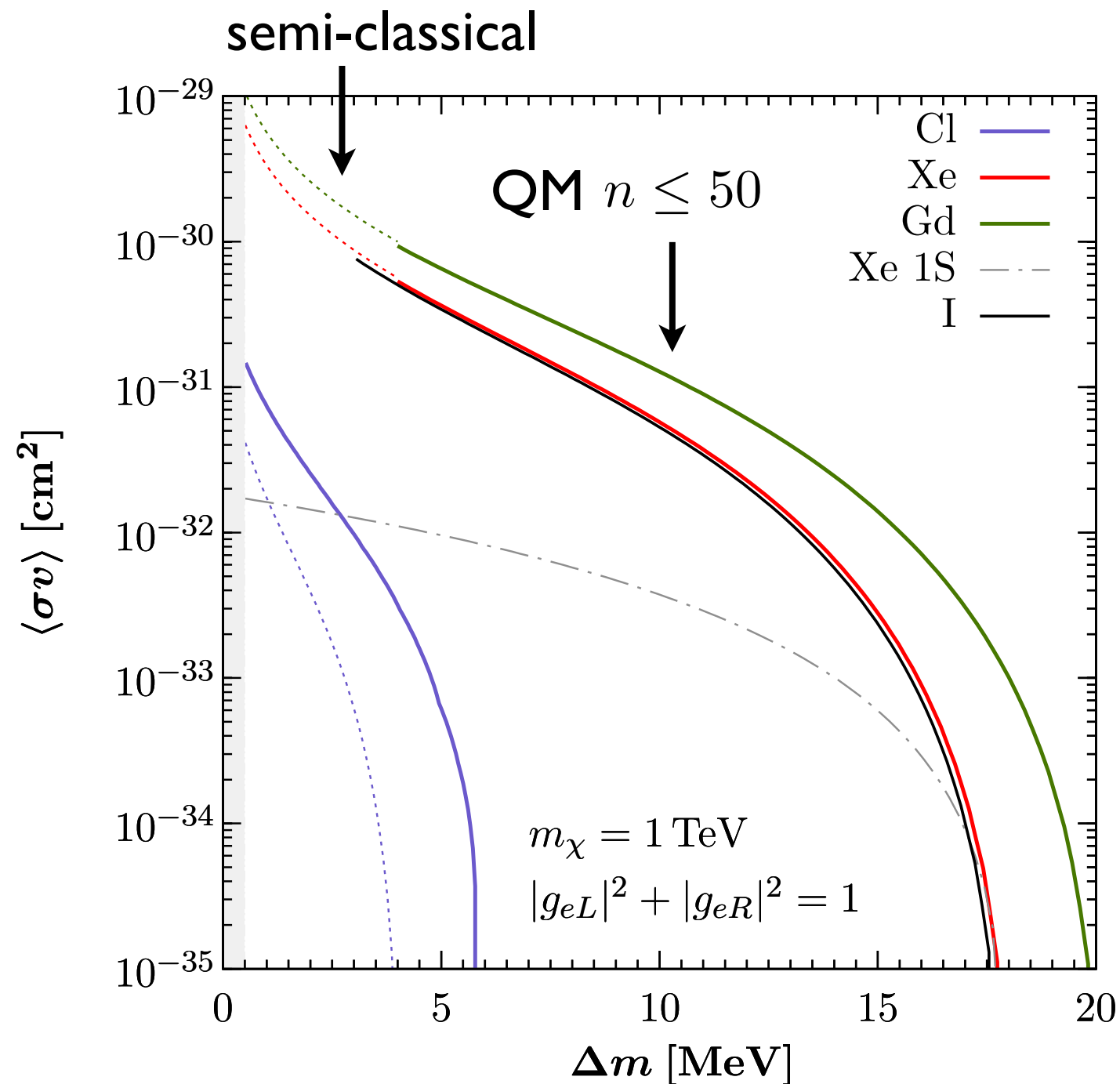=> for heavy nuclei one must include n = 50...100...!

Recombination
Case A

- if so many quantum states are accessible we approach a semi-classical limit:

- integration of fly-by time when $r < r_b$ gives rate for transition
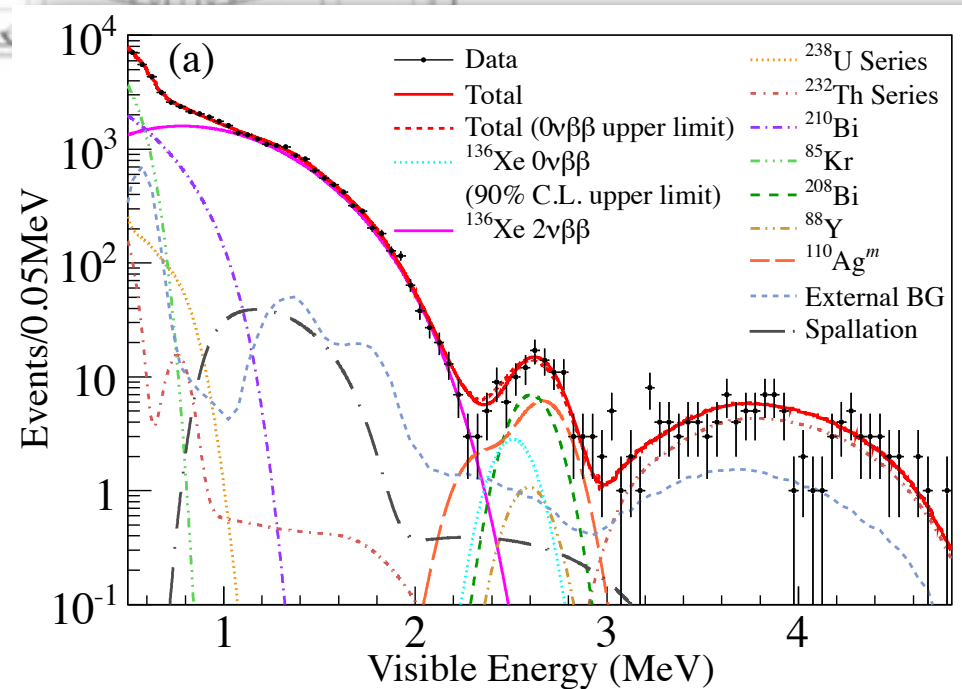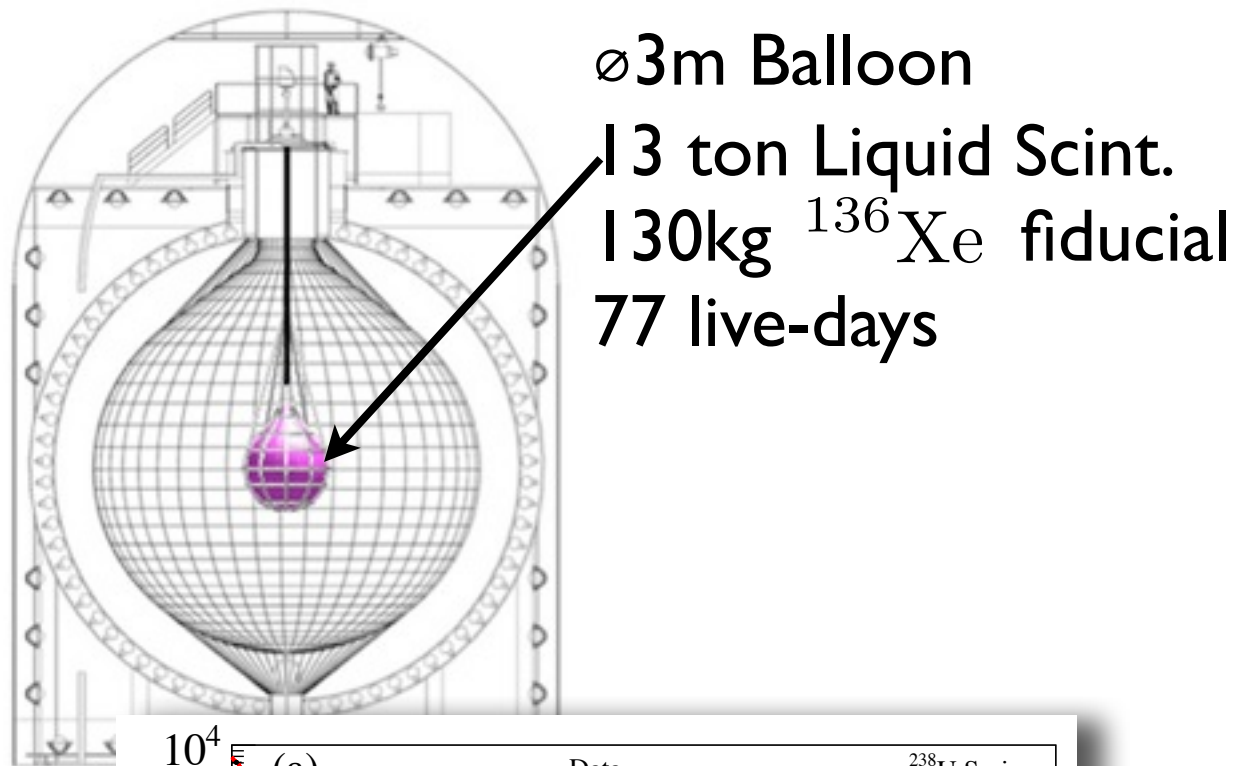
=> semi-classical cross section

$$V(r_b) + \Delta m < 0$$

"critical zone"

X^0

nucleus

The correspondence principle at work
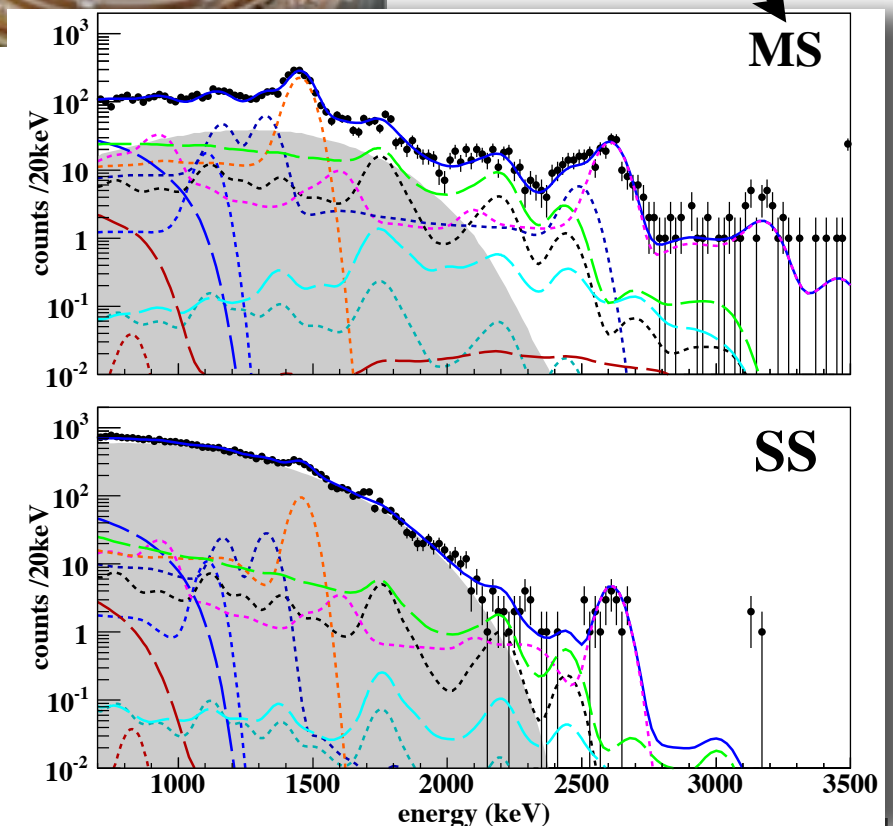
^{136}Xe: Kamland-Zen and EXO-200

- ## Kamland-Zen

∅3m Balloon
13 ton Liquid Scint.
130kg ^{136}Xe fiducial
77 live-days

(a)

Events/0.05MeV

- Data
- Total
- Total (0νββ upper limit)
- ^{136}Xe 0νββ
  (90% C.L. upper limit)
- ^{136}Xe 2νββ
- ^{238}U Series
- ^{232}Th Series
- ^{210}Bi
- ^{85}Kr
- ^{208}Bi
- ^{88}Y
- $^{110}Ag^m$
- External BG
- Spallation

Visible Energy (MeV)
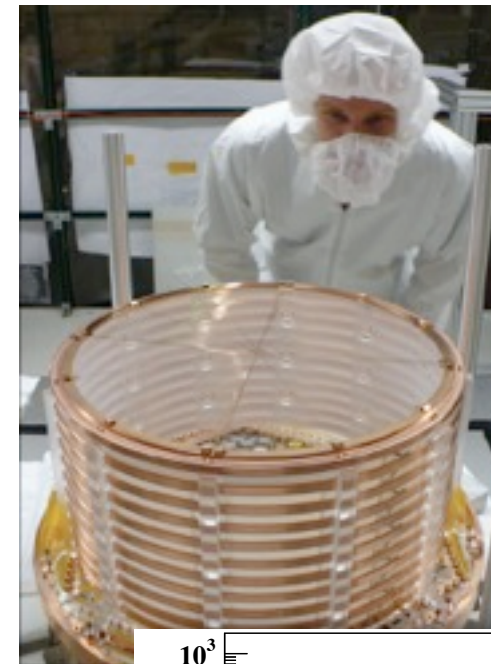
- ## EXO-200

Time Projection
Chamber (TPC)
33 kg x 1 yr

"multi-site"

MS

SS

counts /20keV

energy (keV)

Constraints
EXO-200

χ

e^+ e^- $\gamma\gamma$

Xe

$(\tilde{\tau}^- \mathrm{Xe})^*$

$(\tilde{\tau}^- \mathrm{Xe})_0 + \gamma$'s
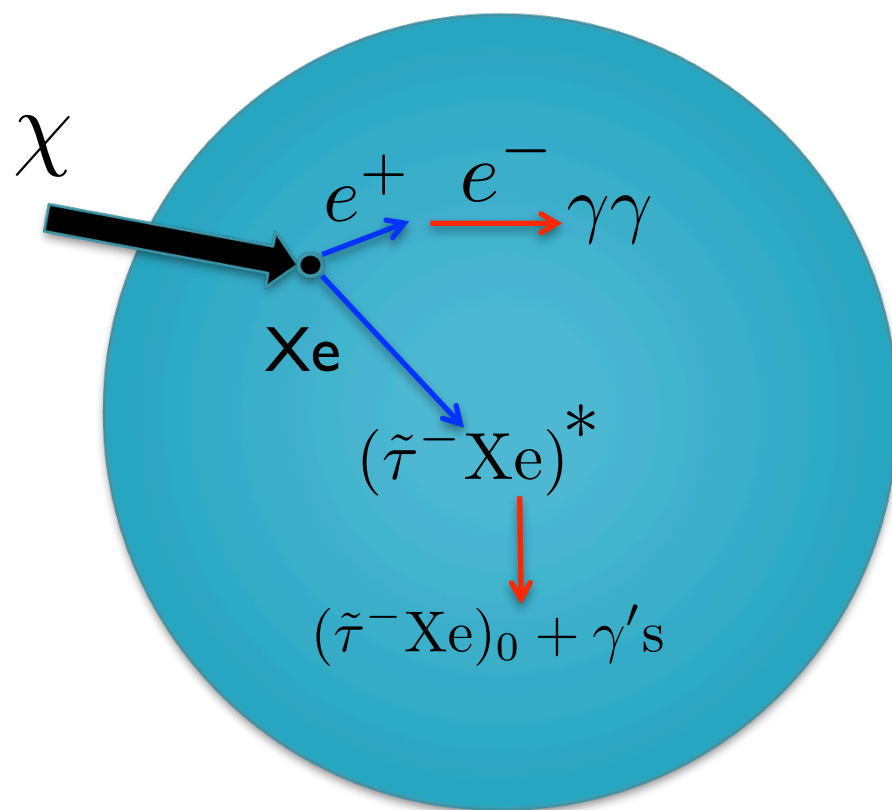
EXO200, Xenon chamber

- spatial EXO resolution ~ 1cm

- "Multiple Site" event because MeV-scale gamma-rays have a mean free path of ~ 6 cm

- total deposited energy (recoil of the bound states negligible)
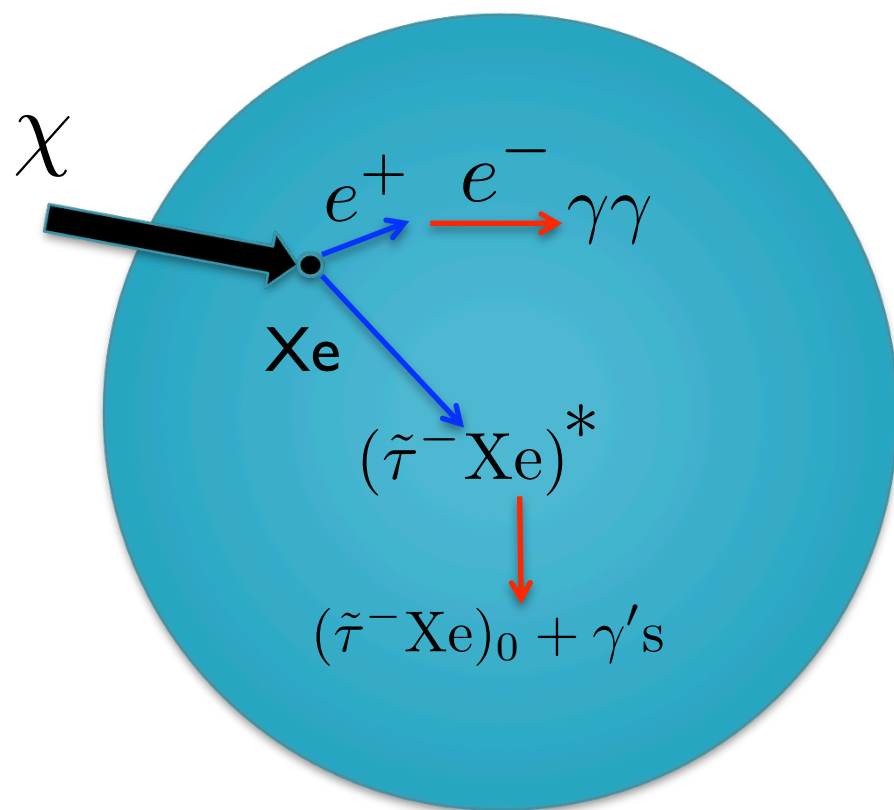
$$E_{\mathrm{tot}} = E_b^{(0)} - \Delta m + m_e$$
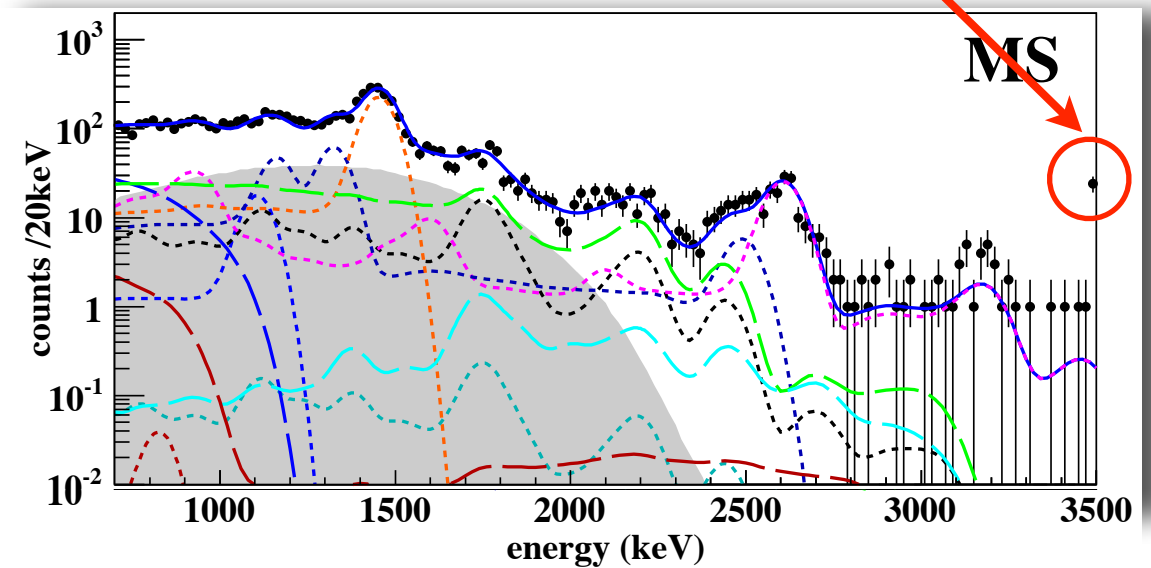
$$E_b \approx 18\,\mathrm{MeV}$$
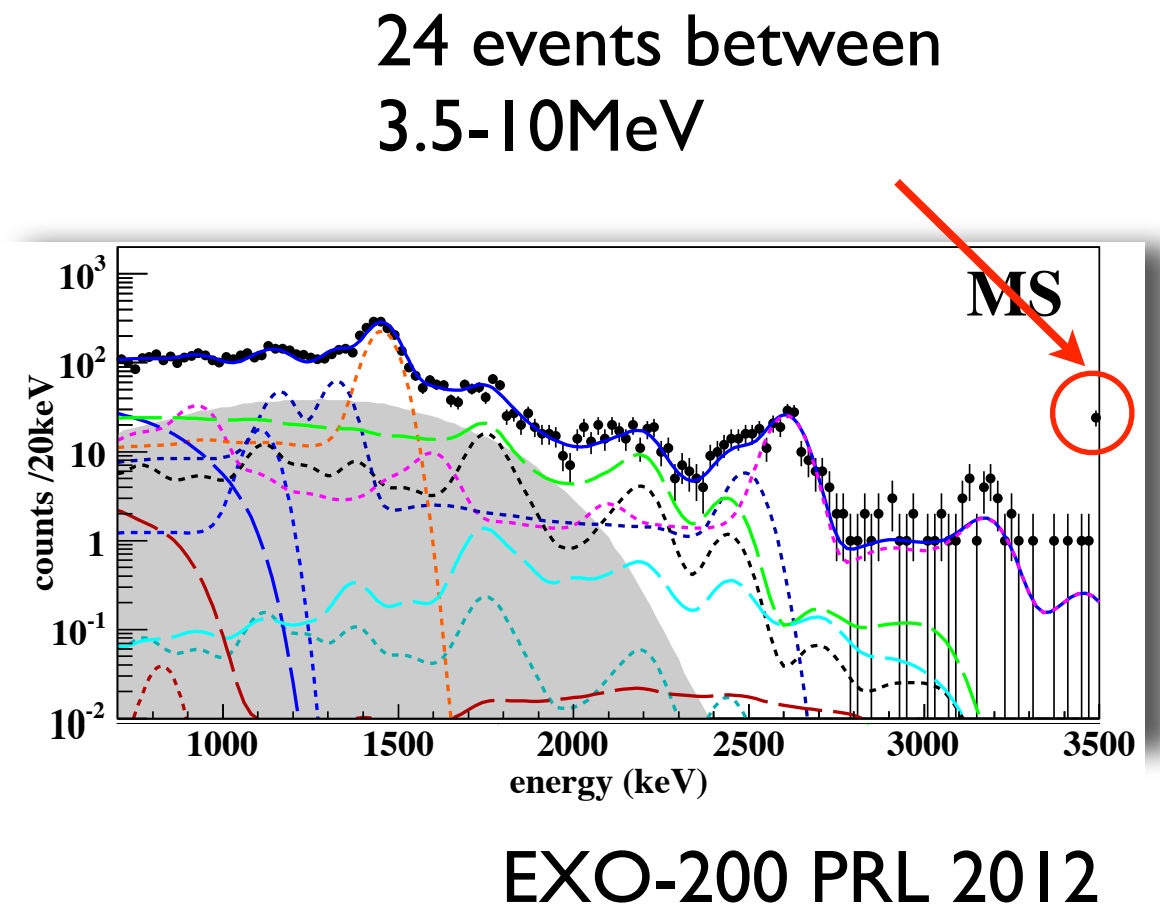
- monochromatic spectrum

Constraints
EXO-200

χ

e^+ e^- $\gamma\gamma$

Xe

$(\tilde{\tau}^-\text{Xe})^*$

$(\tilde{\tau}^-\text{Xe})_0 + \gamma'\text{s}$

EXO200, Xenon chamber

24 events between
3.5-10MeV

MS

counts /20keV

energy (keV)

EXO-200 PRL 2012

Constraints
EXO-200

$$\Gamma_{\tilde{\tau}} \simeq \frac{\sqrt{\Delta m^2 - m_e^2}}{4\pi m_\chi}(\Delta m + m_e)(|g_{eL}|^2 + |g_{eR}|^2)$$

EXO-200

24 events between
3.5-10MeV

MS

EXO-200 PRL 2012
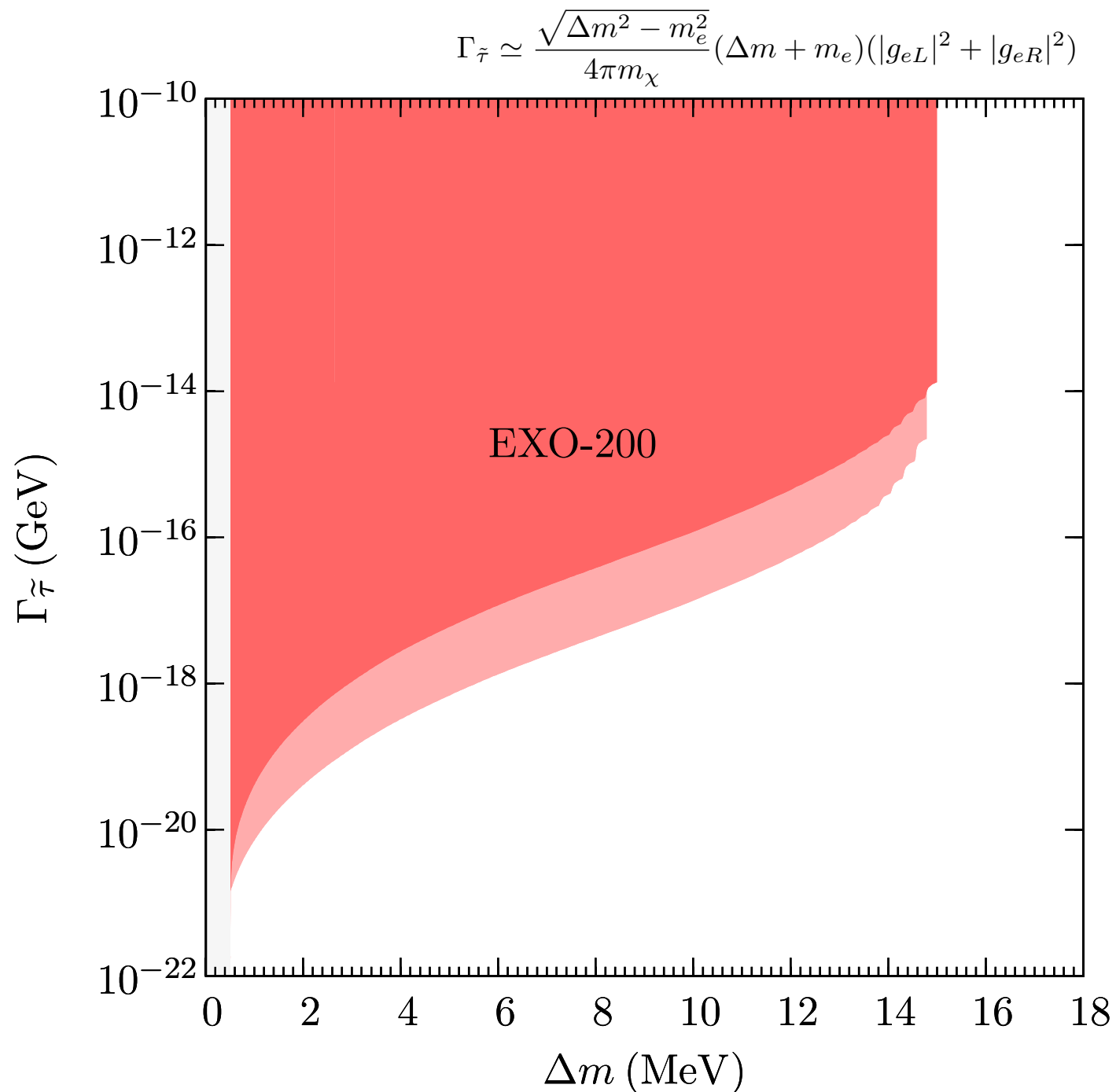
Constraints
Kamland-Zen
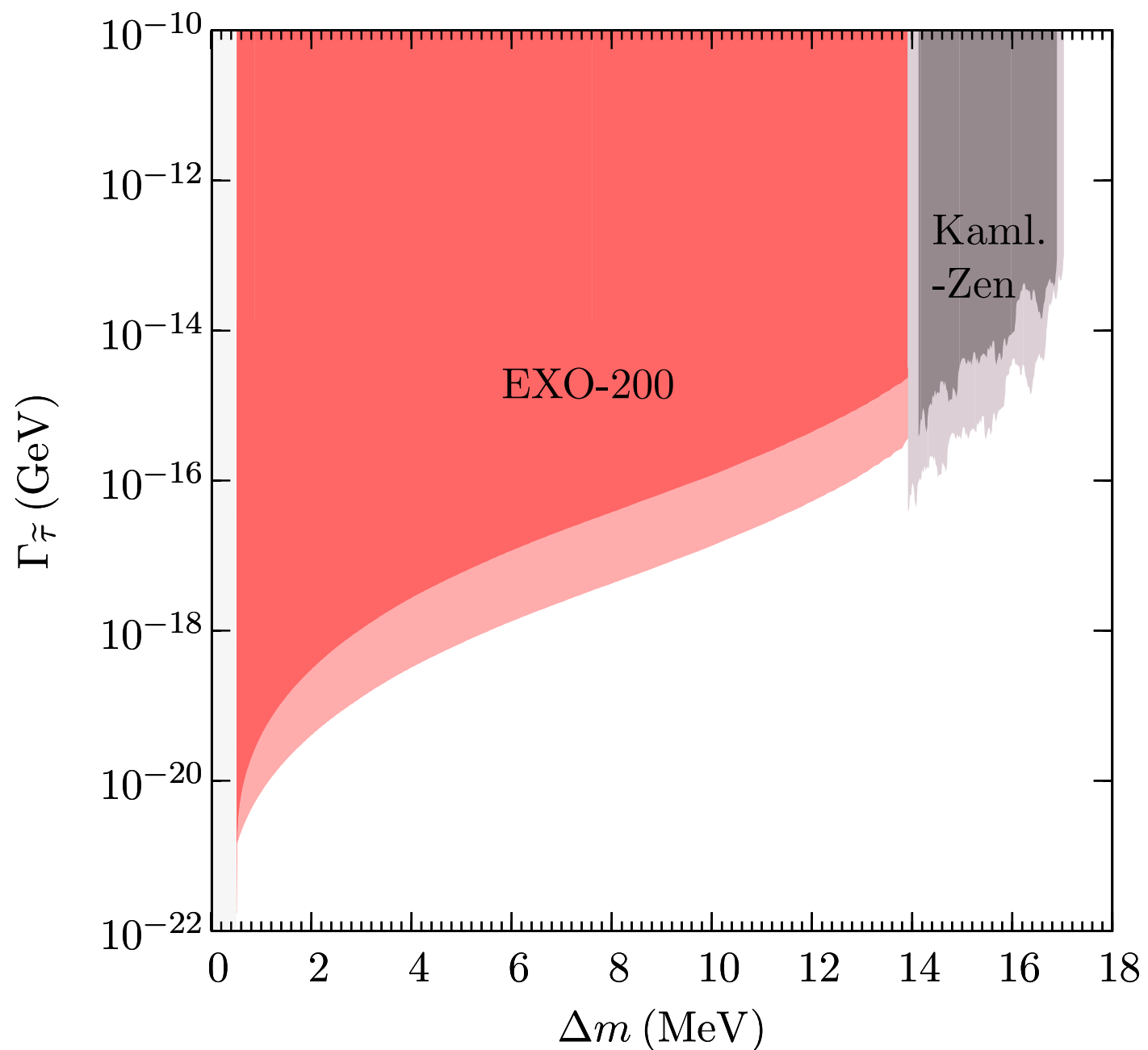
Kamland-Zen PRL 2012

Constraints
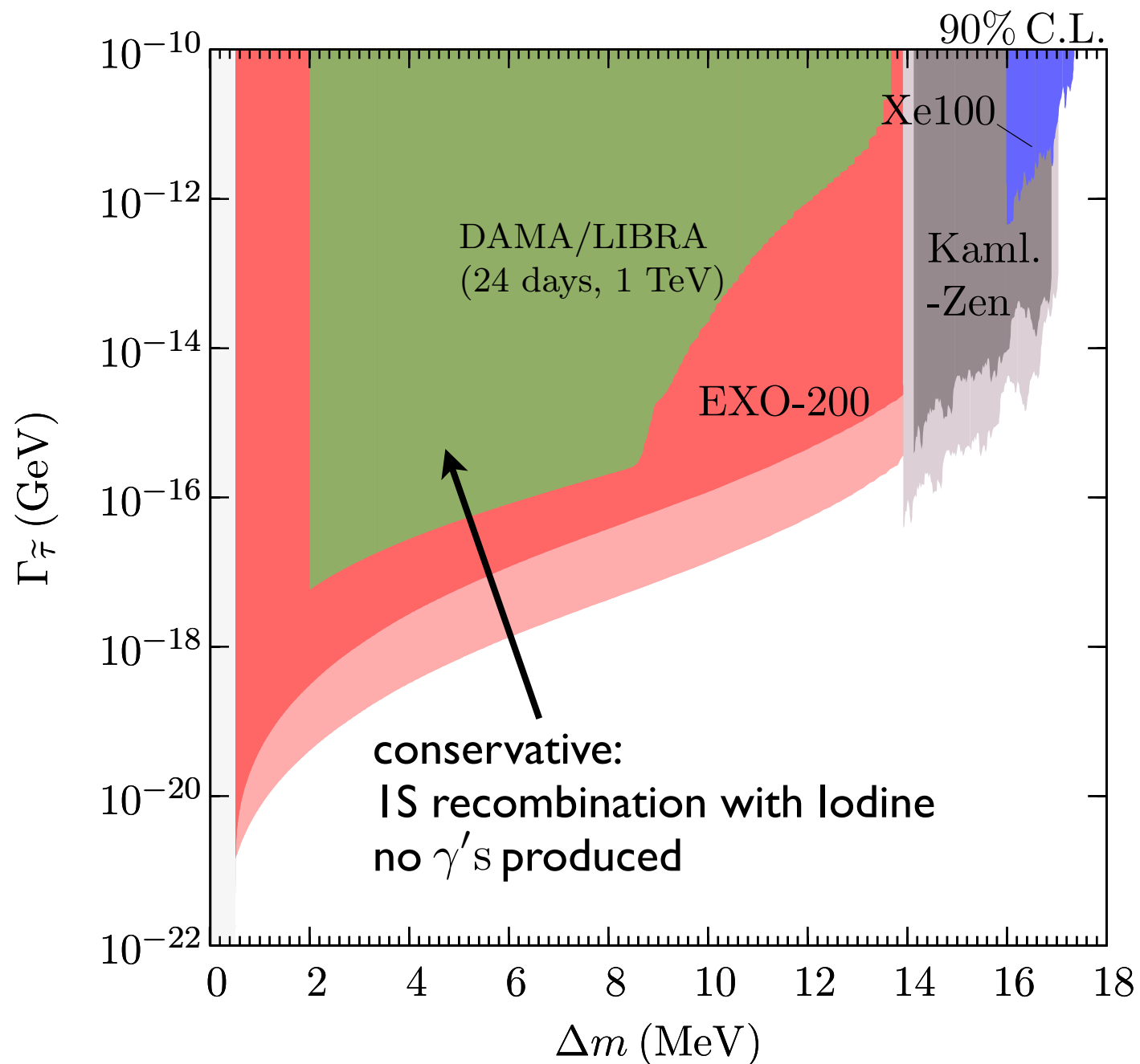## Dark Matter experiments

Xe100

Kaml.
-Zen

EXO-200

$\Gamma_{\tilde{\tau}}$ (GeV)

Δm (MeV)
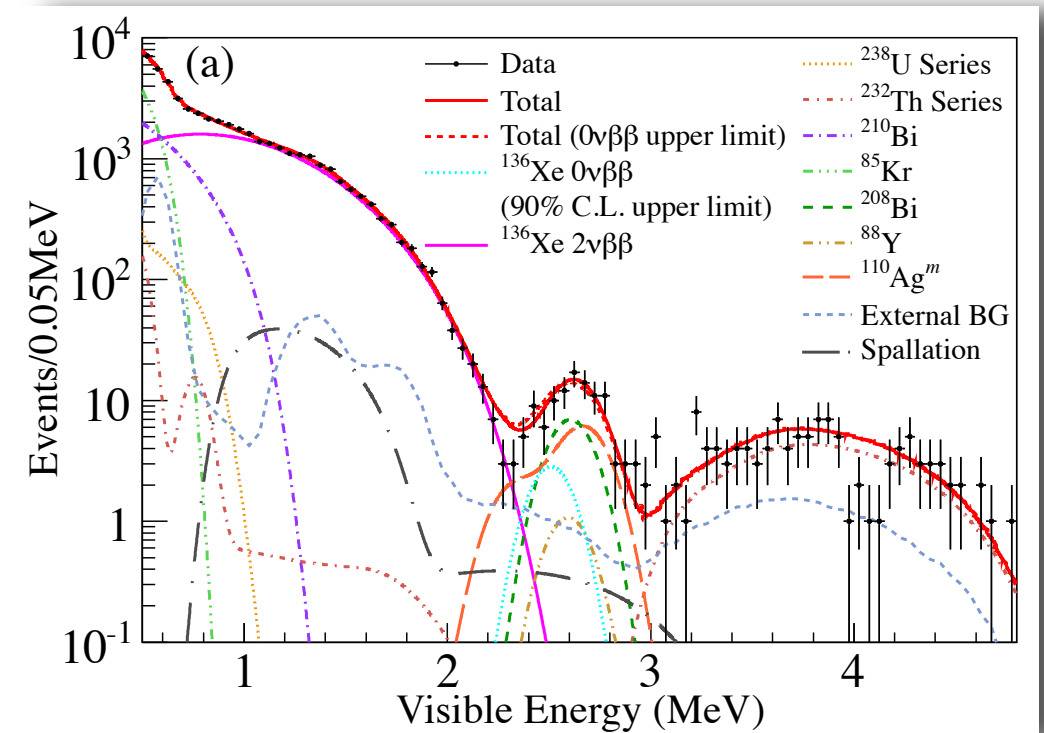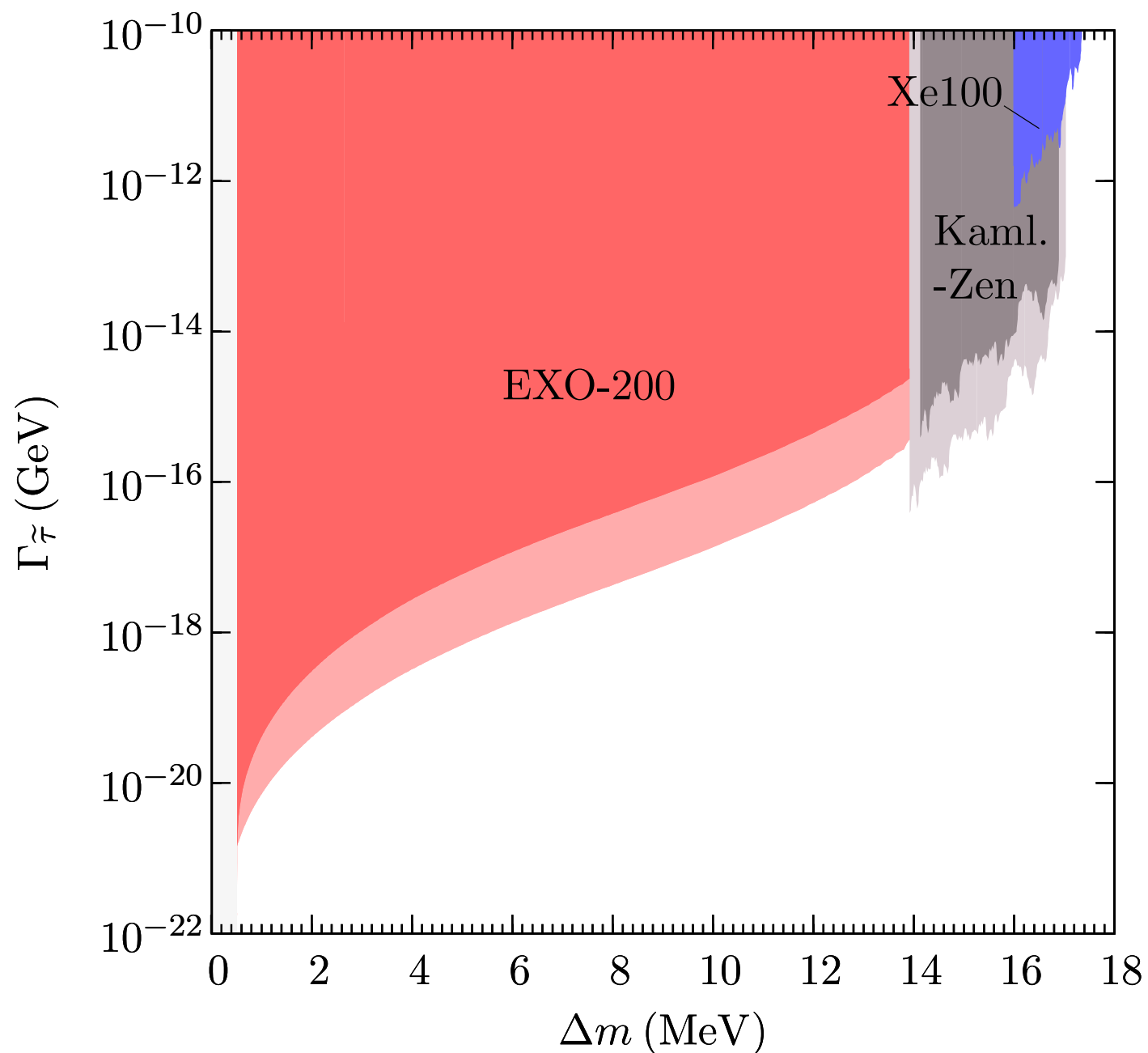
Xenon100 PRD 2011 study of
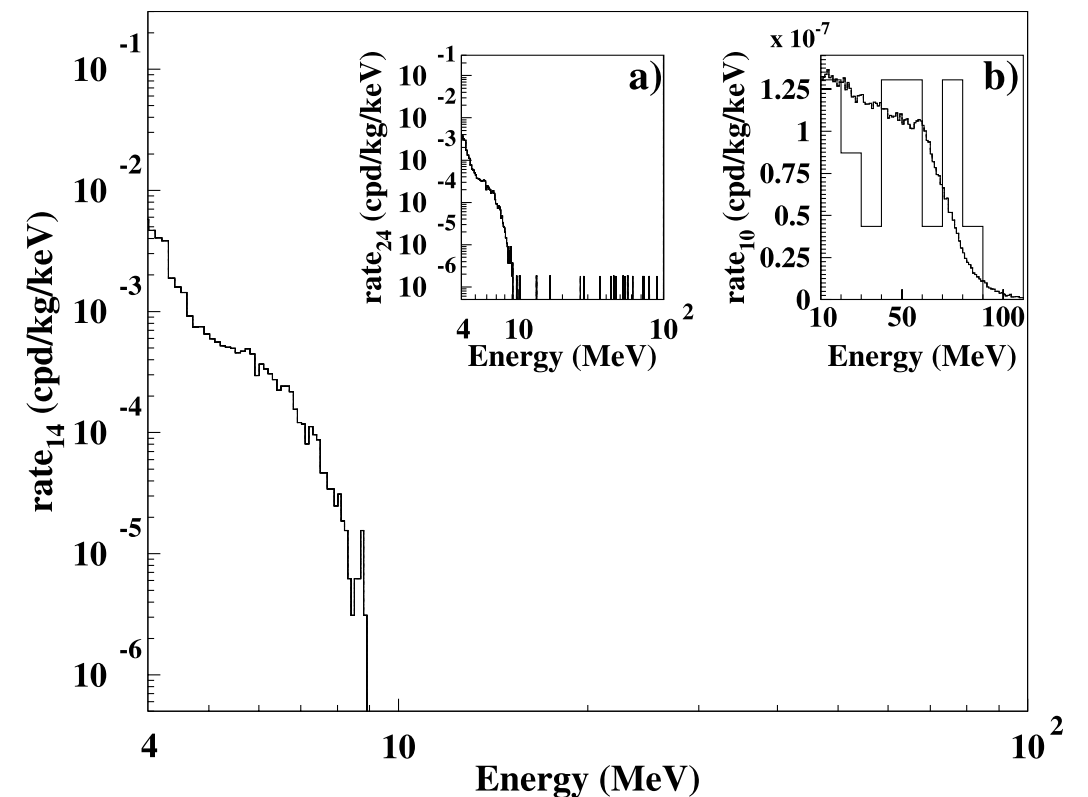electromagnetic background
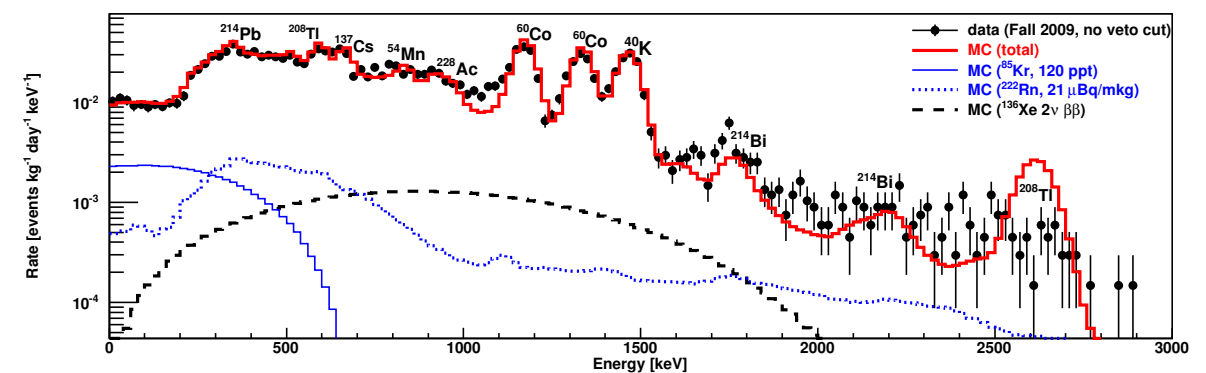
Constraints
Dark Matter experiments

DAMA NaI(Tl)

New search for processes violating the Pauli exclusion principle in sodium and in iodine
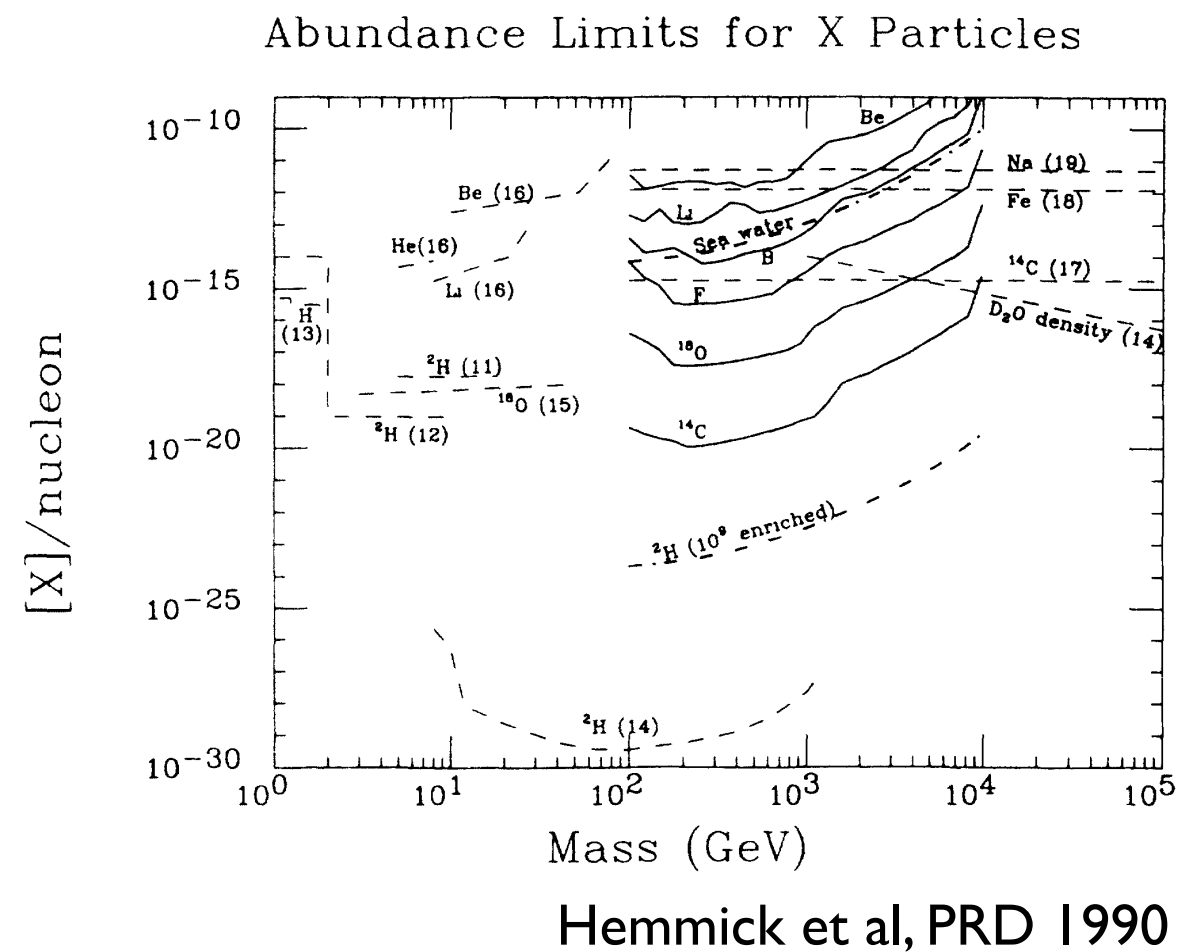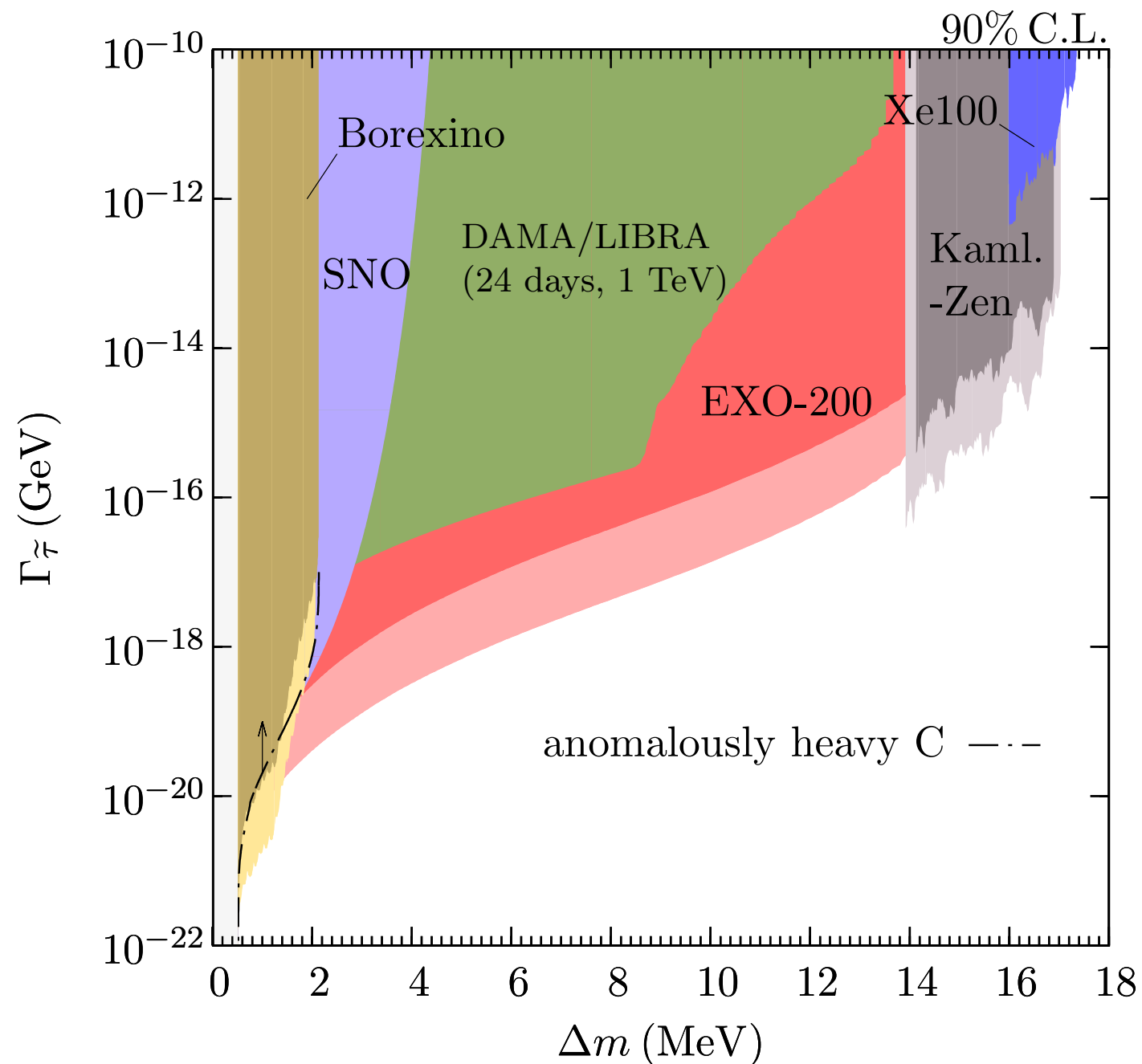
R. Bernabei[1,2,a], P. Belli[2], F. Cappella[3,4], R. Cerulli[5], C.J. Dai[6], A. d'Angelo[3,4], H.L. He[6], A. Incicchitti[4], H.H. Kuang[6], X.H. Ma[6], F. Montecchia[1,2], F. Nozzoli[1,2], D. Prosperi[3,4], X.D. Sheng[6], Z.P. Ye[6,7]
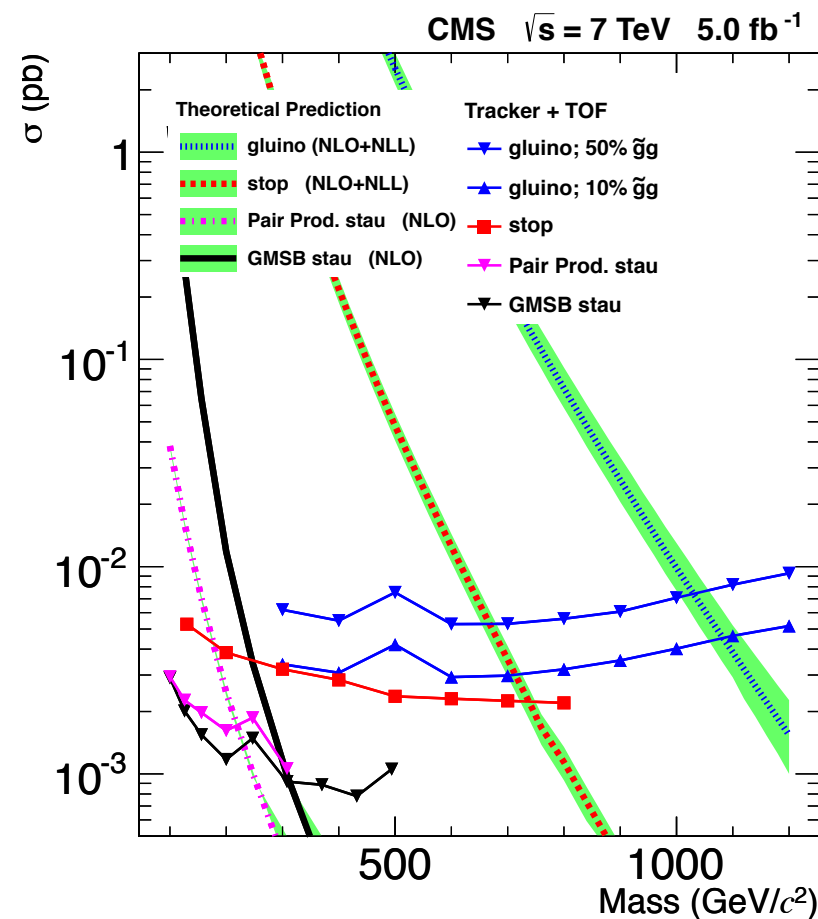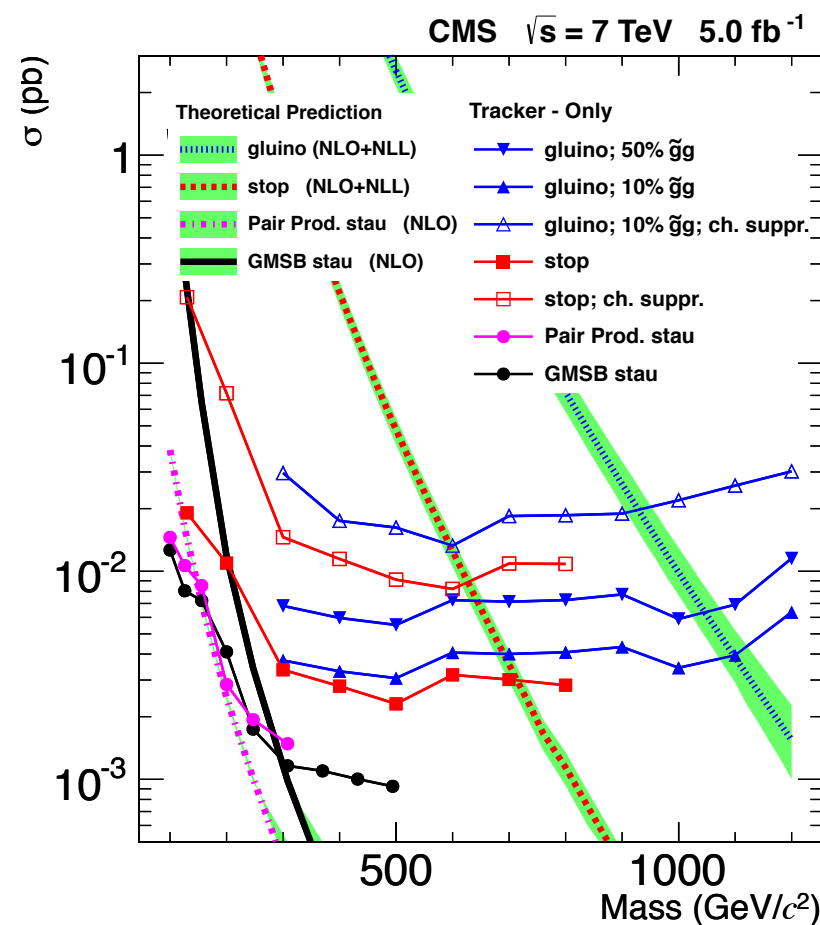

only 22 days out of 12 years

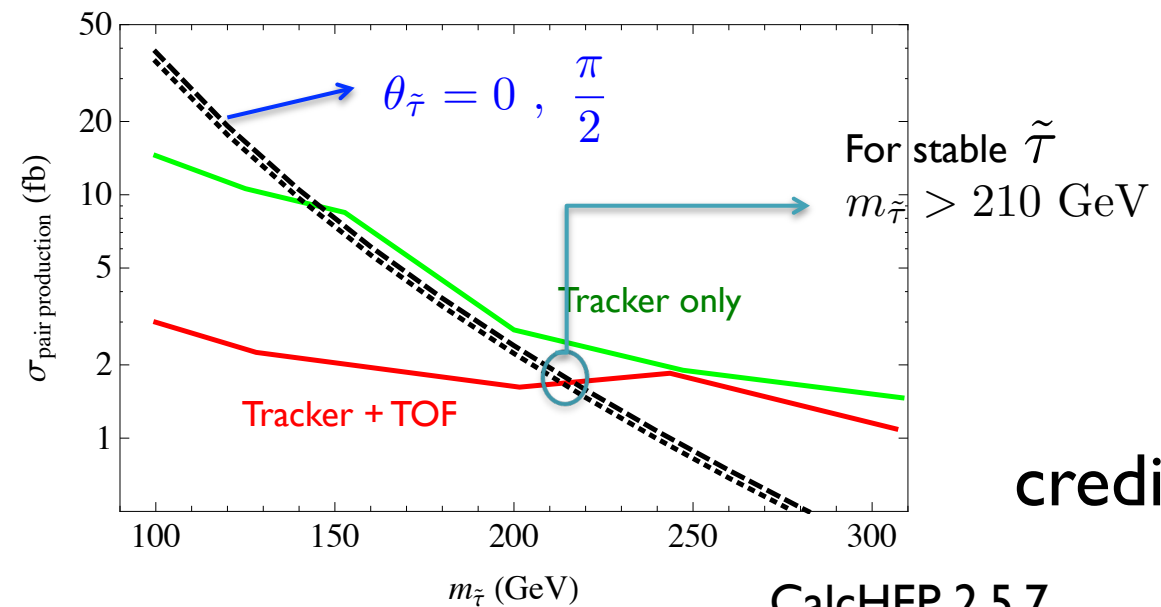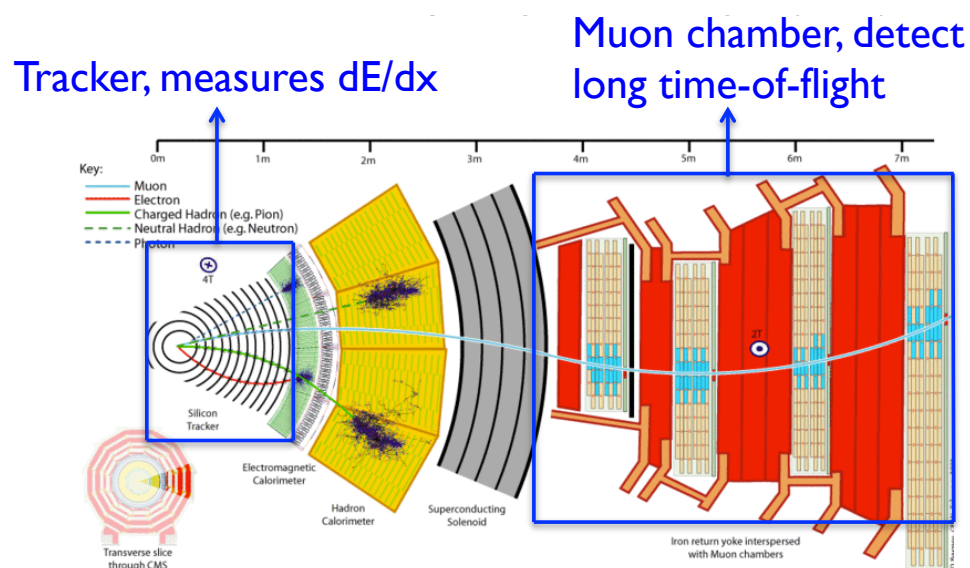# Constraints
anomalously heavy nuclei

anomalously heavy C — · —

Abundance Limits for X Particles

Hemmick et al, PRD 1990

CMS collider constraint

CMS √s = 7 TeV 5.0 fb⁻¹

CMS √s = 7 TeV 5.0 fb⁻¹

- we only consider the stau pair production channel

- limit depends on stau mass; no limit above 210GeV

arXiv:1205.0272

$\tilde{\tau}$

$\tilde{\tau}_L$ $\tilde{\tau}_R$

Tracker, measures dE/dx

Muon chamber, detect long time-of-flight

$\theta_{\tilde{\tau}} = 0$, $\frac{\pi}{2}$

For stable $\tilde{\tau}$
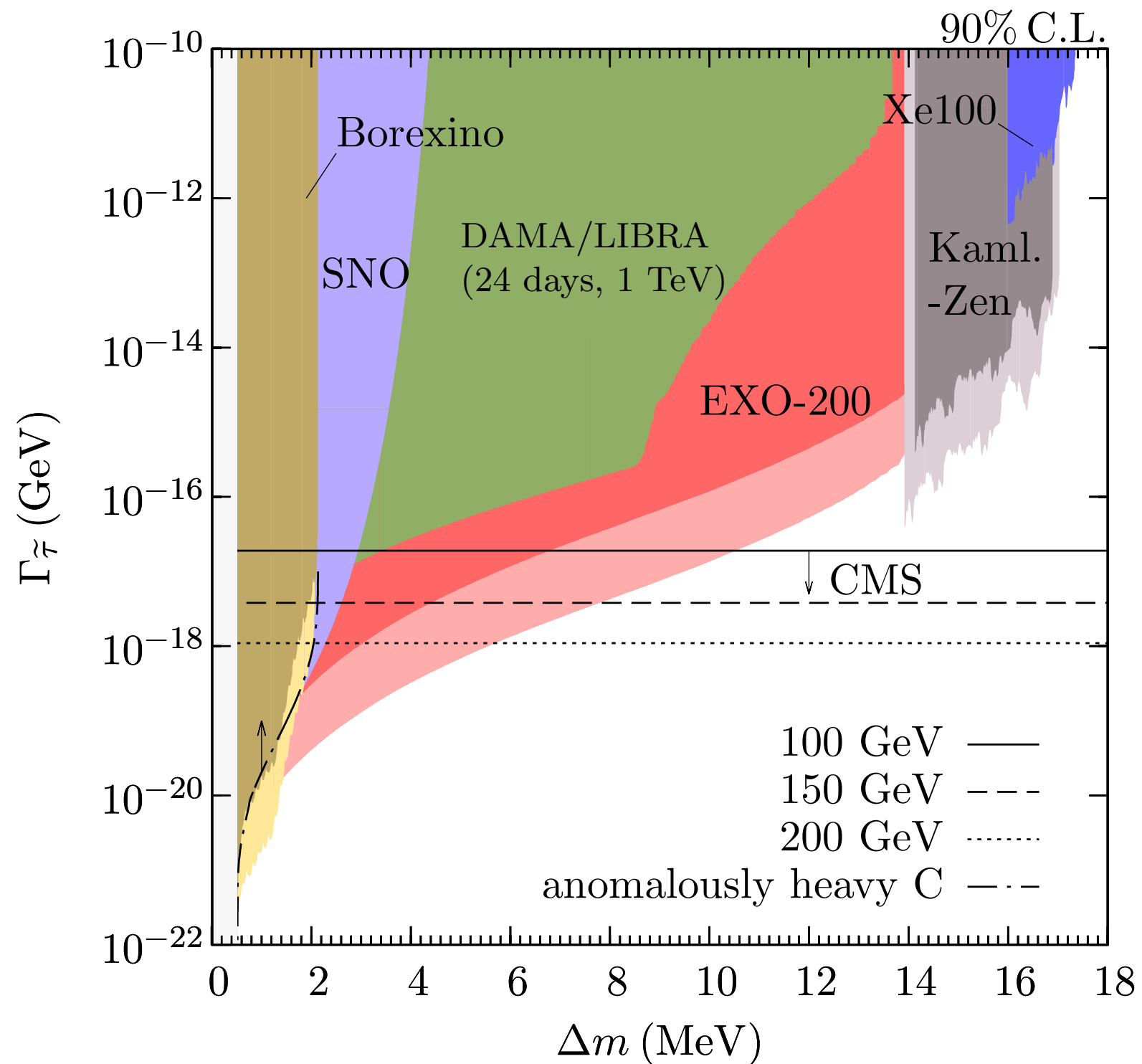$m_{\tilde{\tau}} > 210$ GeV

Tracker only

Tracker + TOF

credit: Haipeng
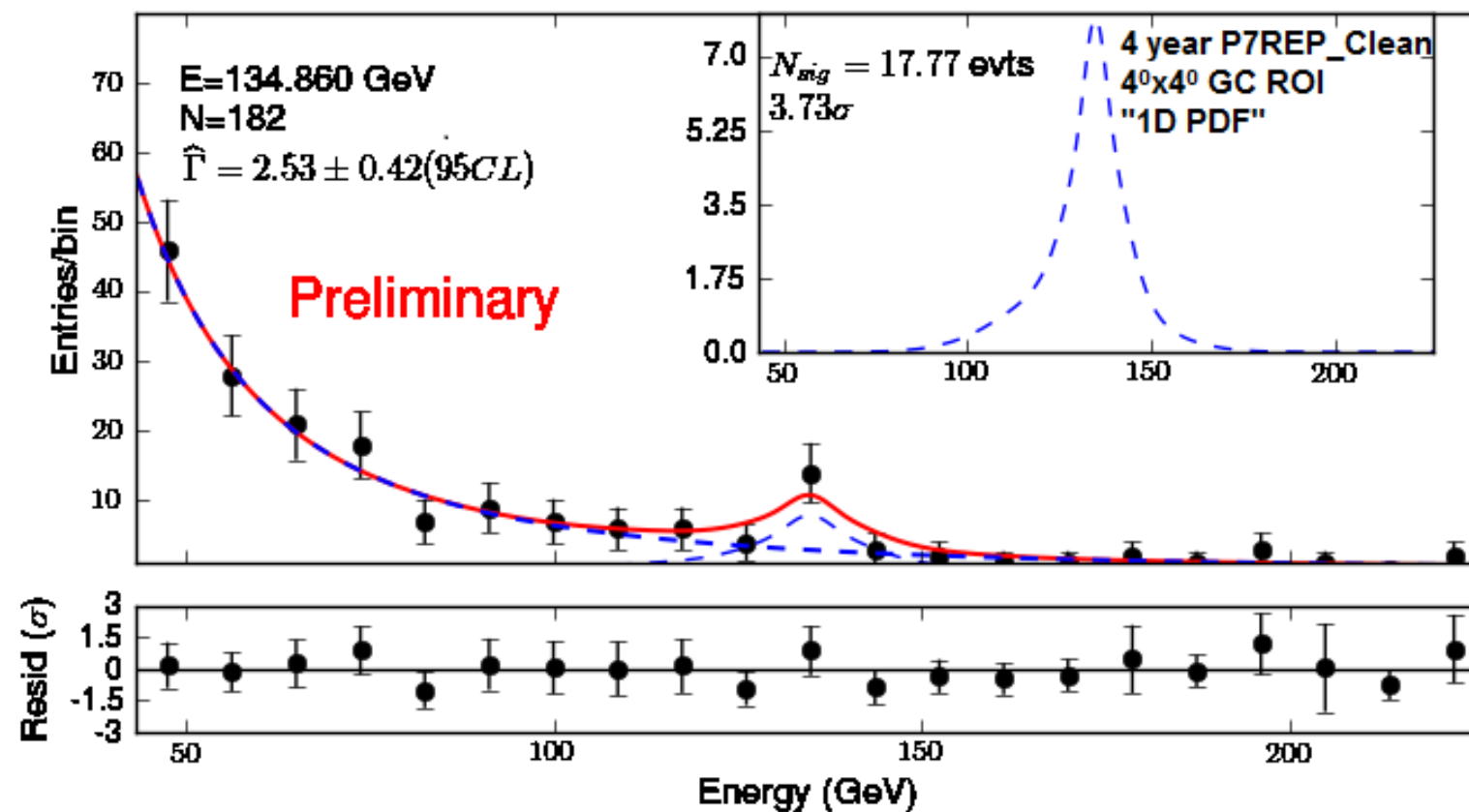
CalcHEP 2.5.7

Constraints
summary

An application:
Fermi 130 GeV gamma ray line

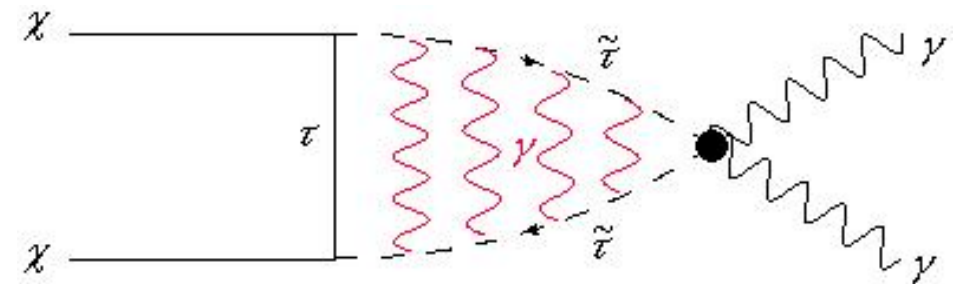unexplained line feature in gamma rays from the galactic center

130-135 GeV

Bringman et al. 2012, Weniger 2012,...
Bloom et al. 2013 (Fermi Collab.)

An application:
Fermi 130 GeV gamma ray line

- Emission from GC requires annihilation cross section $\langle \sigma v \rangle_{\gamma\gamma} \sim 10^{-27} \,\mathrm{cm}^3/\mathrm{s}$

- enhancement possible through "stauonium resonance" via
  $$\overline{\chi}(g_L P_L + g_R P_R)\tau \widetilde{\tau}^\dagger + \mathrm{h.c.}$$
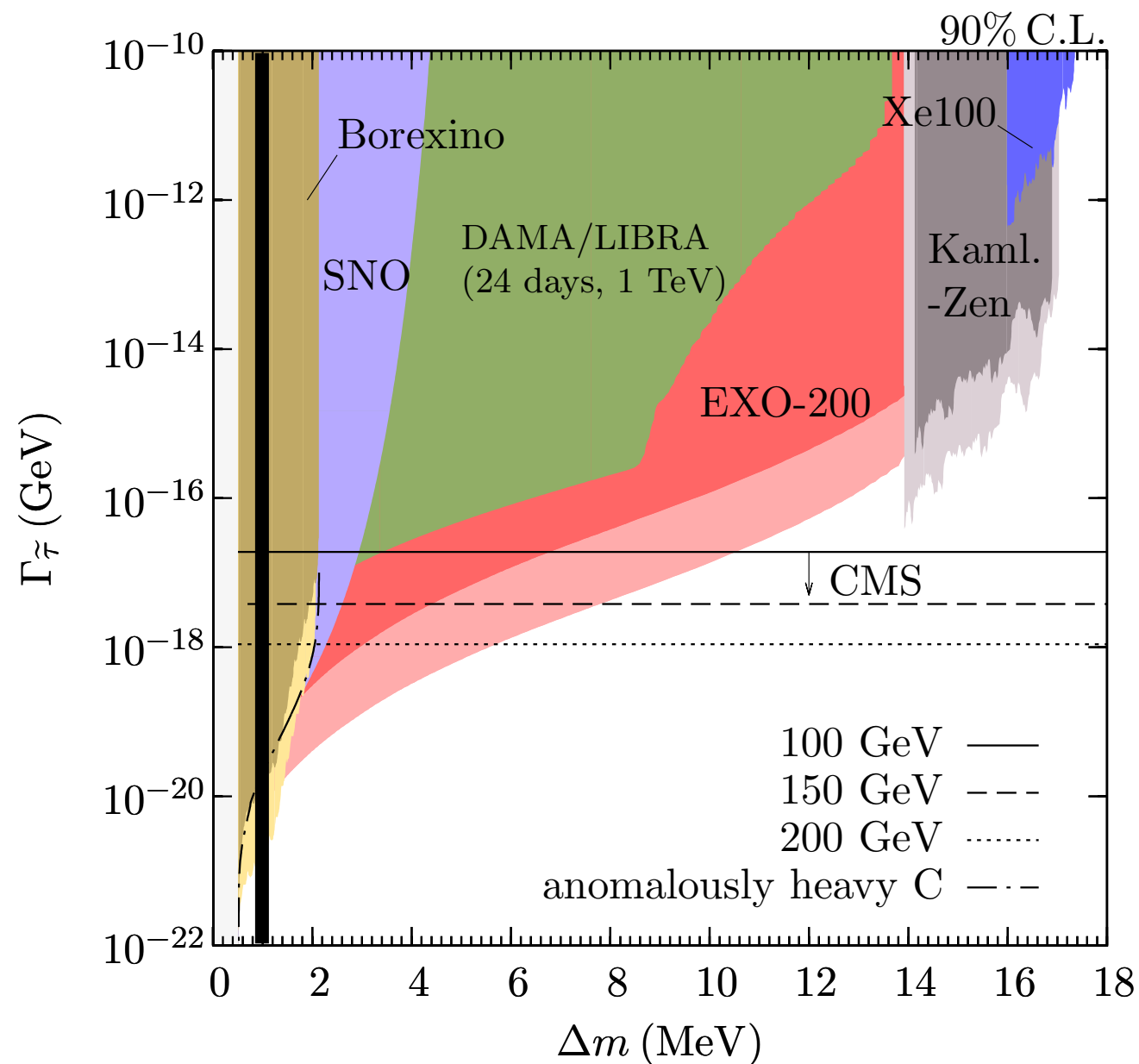

$\widetilde{\tau}^+ \widetilde{\tau}^-$ bound state

$E_k + E_{\mathrm{binding}} - 2\Delta m \approx 0$

$2 \times 130\,\mathrm{GeV} = 2m_\chi$

$2m_{\widetilde{\tau}}$

$E_k \approx 0.1\,\mathrm{MeV}$

$E_{\mathrm{binding}}^{(0)} = \dfrac{\alpha_{\mathrm{em}}^2 m_{\widetilde{\tau}}}{4} \approx 1.7\,\mathrm{MeV}$

$E_b(\widetilde{\tau}^+\widetilde{\tau}^-) \simeq 2\Delta m$

$\Delta m \lesssim 0.9\,\mathrm{MeV}$

resonance condition

$\mathrm{Re}\,g_L \approx \mathrm{Im}\,g_L \approx \mathrm{Re}\,g_R \approx \mathrm{Im}\,g_R \approx 0.06$

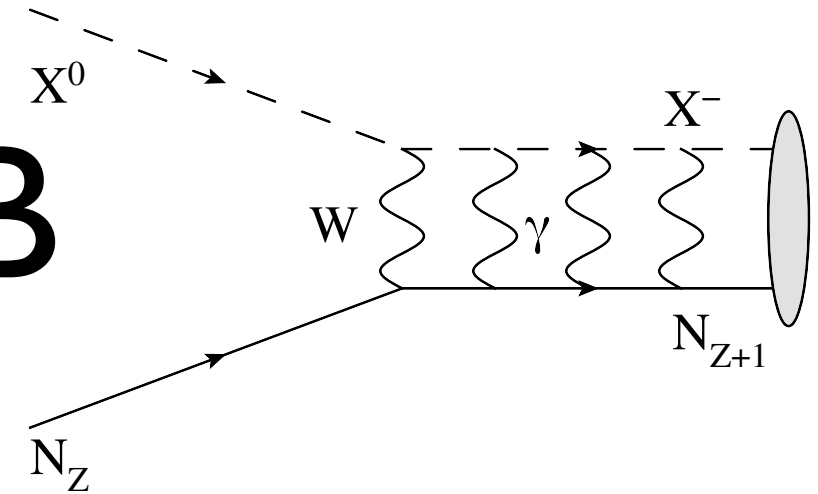$\Rightarrow \Delta m \lesssim 0.9\,\mathrm{MeV}$

An application:
Fermi 130 GeV gamma ray line

Fermi line explanation excluded from the combined constraint from neutrino experiments and CMS

Recombination - Case B

- encouraged by success of our semi-classical calculation for Case A, use it for Case B (nuclear transmutation $N_Z \to N_{Z+1}$)

- Step 1: calculate cross section for $X^0 n \to X^- p$

- Step 2: use Fermi gas model for density and momentum distribution of n and p inside the nucleus; consideration of fly-by time again gives cross section.

- Note: because of Pauli-blocking, part of the potential energy must be invested to lift p above the Fermi surface of N_{Z+1}
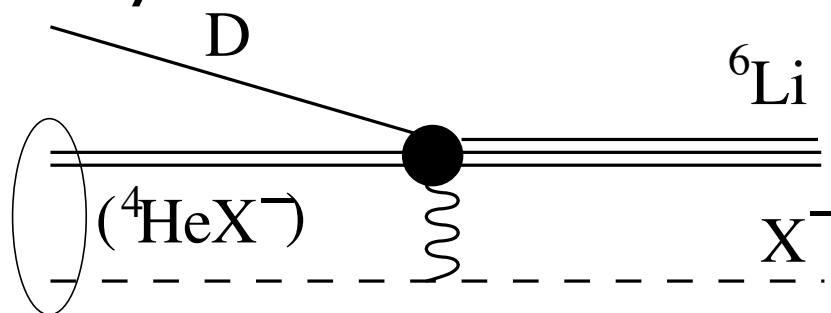
cosmological constraints
long-lived charged relics

- CHAMPs during BBN lead to severe overproduction of 6Li from bound states with He.

standard BBN:
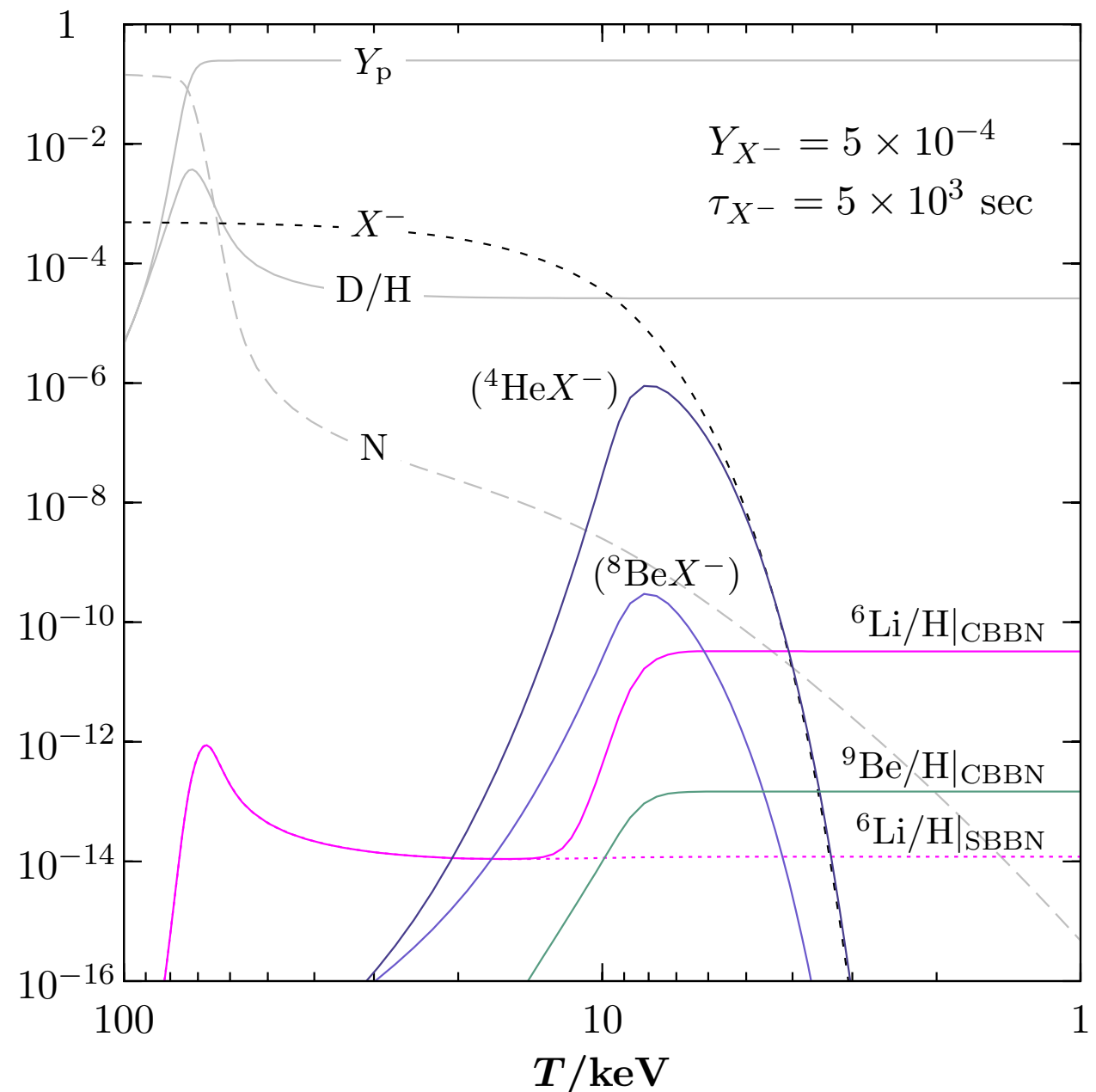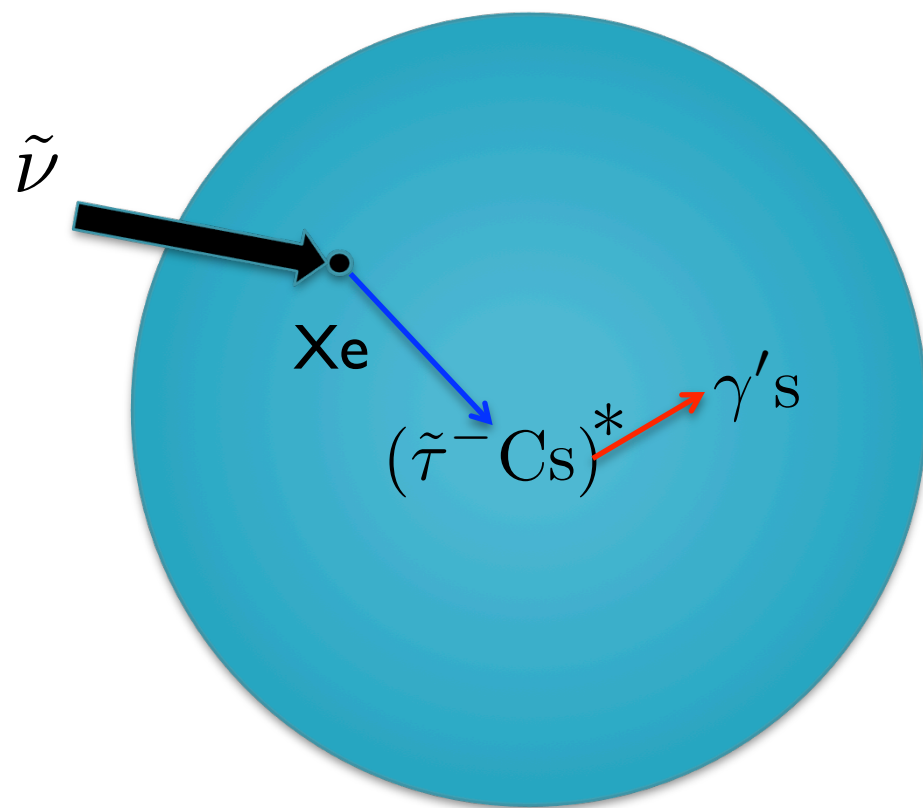

catalyzed BBN:

$Y_{X^-} = 5 \times 10^{-4}$

$\tau_{X^-} = 5 \times 10^3 \text{ sec}$
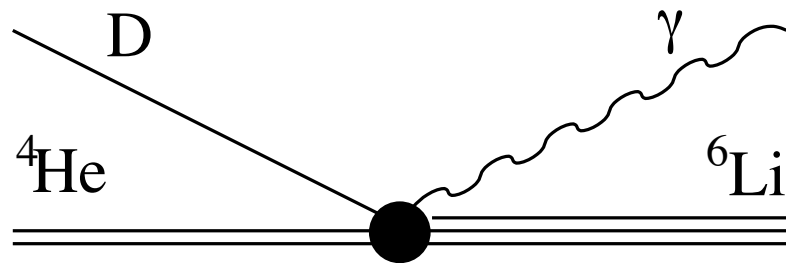
Pospelov PRL 2006

Pospelov, Pradler Ann.Rev.Nucl.Part.Sci. 2010

Constraints
case B

$\tilde{\nu}$

Xe

$(\tilde{\tau}^- Cs)^*$

$\gamma's$

EXO200, Xenon chamber

long lived
excited state:

$$\Gamma_{\tilde{\tau}} \propto \frac{\Delta m^5}{m_W^4}$$

90% C.L.

Xe100

$g_{\text{eff}} = g_2$

EXO-200

Kaml. -Zen

1 s

10^2 s

10^4 s

CBBN

10^6 s

g_{eff}

1

0.1

0.01

Δm (MeV)

0 2 4 6 8 10 12 14 16 18
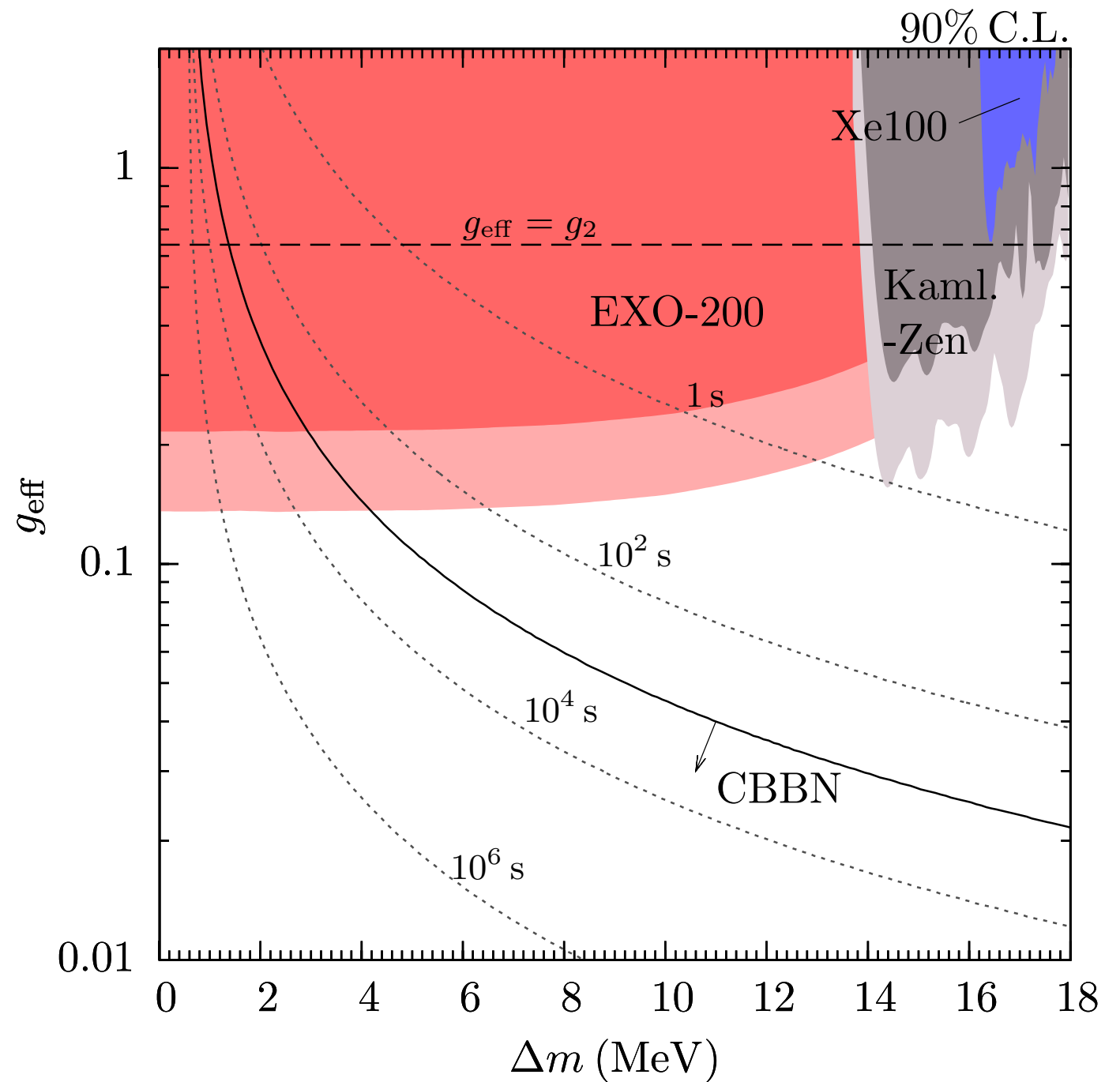
Conclusions

- Entertained a model with a new neutrino that couples with stronger-than-weak interactions to quarks, guarded by the "oscillation portal"

  yields alternative explanation to the dark matter direct detection anomalies

  in some variants of the model, it may also have interesting implications for the recent non-atmospheric (sub)-PeV IceCube neutrino obs.

- Rare event searches with good MeV sensitivity can test the co-annihilation regime where DM has electromagnetic charged excitations---in regions that are out of kinematic reach at LHC.

Thank you!